

1981

The Kara Sea: geologic structure and water characteristics

Donald B. Milligan

College of William and Mary - Virginia Institute of Marine Science

Follow this and additional works at: <https://scholarworks.wm.edu/etd>



Part of the [Geology Commons](#)

Recommended Citation

Milligan, Donald B., "The Kara Sea: geologic structure and water characteristics" (1981). *Dissertations, Theses, and Masters Projects*. Paper 1539616777.

<https://dx.doi.org/doi:10.25773/v5-qb1r-8s17>

This Dissertation is brought to you for free and open access by the Theses, Dissertations, & Master Projects at W&M ScholarWorks. It has been accepted for inclusion in Dissertations, Theses, and Masters Projects by an authorized administrator of W&M ScholarWorks. For more information, please contact scholarworks@wm.edu.

INFORMATION TO USERS

This was produced from a copy of a document sent to us for microfilming. While the most advanced technological means to photograph and reproduce this document have been used, the quality is heavily dependent upon the quality of the material submitted.

The following explanation of techniques is provided to help you understand markings or notations which may appear on this reproduction.

1. The sign or "target" for pages apparently lacking from the document photographed is "Missing Page(s)". If it was possible to obtain the missing page(s) or section, they are spliced into the film along with adjacent pages. This may have necessitated cutting through an image and duplicating adjacent pages to assure you of complete continuity.
2. When an image on the film is obliterated with a round black mark it is an indication that the film inspector noticed either blurred copy because of movement during exposure, or duplicate copy. Unless we meant to delete copyrighted materials that should not have been filmed, you will find a good image of the page in the adjacent frame. If copyrighted materials were deleted you will find a target note listing the pages in the adjacent frame.
3. When a map, drawing or chart, etc., is part of the material being photographed the photographer has followed a definite method in "sectioning" the material. It is customary to begin filming at the upper left hand corner of a large sheet and to continue from left to right in equal sections with small overlaps. If necessary, sectioning is continued again—beginning below the first row and continuing on until complete.
4. For any illustrations that cannot be reproduced satisfactorily by xerography, photographic prints can be purchased at additional cost and tipped into your xerographic copy. Requests can be made to our Dissertations Customer Services Department.
5. Some pages in any document may have indistinct print. In all cases we have filmed the best available copy.

University
Microfilms
International

300 N. ZEEB RD., ANN ARBOR, MI 48106

8206124

MILLIGAN, DONALD BRISTOWE

**THE KARA SEA: GEOLOGIC STRUCTURE AND WATER
CHARACTERISTICS**

The College of William and Mary in Virginia

PH.D. 1981

**University
Microfilms
International** 300 N. Zeeb Road, Ann Arbor, MI 48106

PLEASE NOTE:

In all cases this material has been filmed in the best possible way from the available copy.
Problems encountered with this document have been identified here with a check mark .

1. Glossy photographs or pages _____
2. Colored illustrations, paper or print _____
3. Photographs with dark background _____
4. Illustrations are poor copy _____
5. Pages with black marks, not original copy _____
6. Print shows through as there is text on both sides of page _____
7. Indistinct, broken or small print on several pages
8. Print exceeds margin requirements _____
9. Tightly bound copy with print lost in spine _____
10. Computer printout pages with indistinct print _____
11. Page(s) _____ lacking when material received, and not available from school or author.
12. Page(s) _____ seem to be missing in numbering only as text follows.
13. Two pages numbered _____. Text follows.
14. Curling and wrinkled pages _____
15. Other _____

**University
Microfilms
International**

THE KARA SEA:
GEOLOGIC STRUCTURE AND WATER CHARACTERISTICS

A Dissertation

Presented to
The Faculty of the School of Marine Science
Virginia Institute of Marine Science
The College of William and Mary in Virginia

In Partial Fulfillment
Of the Requirements for the Degree of
Doctor of Philosophy

by
Donald B. Milligan

1981

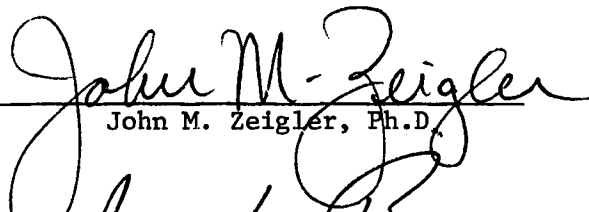
APPROVAL SHEET

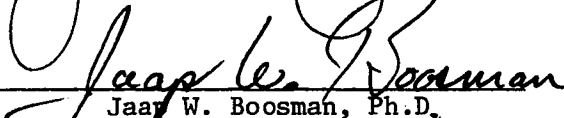
This dissertation is submitted in partial fulfillment of
the requirements for the degree of

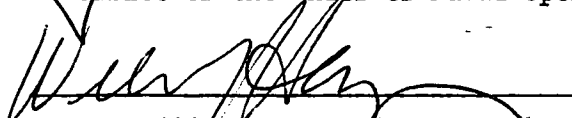
Doctor of Philosophy



Donald B. Milligan


Approved, August 1981


John M. Zeigler, Ph.D.


Jaap W. Boosman, Ph.D.
Office of the Chief of Naval Operations


William J. Hargis, Jr., Ph.D.


Carl H. Hobbs, III


Evon P. Ruzecki, Ph.D.

ACKNOWLEDGEMENTS

This work was carried out by the author as Chief Scientist for the Naval Oceanographic Office aboard the Coast Guard Cutter NORTHWIND (WAGB 282). Appreciation is extended to the naval scientists involved in the survey and to the officers and crew of the NORTHWIND.

I gratefully acknowledge the guidance given by my Chairman, Dr. John Zeigler. Dr. William J. Hargis, Jr., Dr. Evon P. Ruzecki, and Mr. Carl H. Hobbs, III offered invaluable recommendations and critically read this manuscript. I also express my appreciation to Dr. Jaap W. Boosman for his friendship and encouragement to persevere during the interval between collection and final presentation of this manuscript.

Finally, thanks to my daughter, Elizabeth, for typing and proofreading.

TABLE OF CONTENTS

	Page
ACKNOWLEDGEMENTS.....	iii
LIST OF TABLES.....	v
LIST OF FIGURES.....	vi
ABSTRACT.....	viii
FOREWORD.....	2
INTRODUCTION	
Objectives.....	5
Setting.....	5
Methodology.....	7
GEOLOGIC STRUCTURE	
Literature Review.....	18
Discussion of Data.....	22
Conclusions.....	32
WATER CHARACTERISTICS	
Literature Review.....	34
Discussion of Data.....	37
Conclusions.....	48
SUMMARY.....	53
REFERENCES CITED.....	55
APPENDIX A - Detailed Cross Sections of the Water Masses in the Kara Sea.	
APPENDIX B - Areal Distributions of the principal Kara Sea Parameters: Temperature, Salinity, Reactive Silicate, Dissolved Oxygen, Reactive Phosphorus, and pH.	

LIST OF TABLES

Table	Page
I. Siberian Rivers Emptying into the Kara Sea.....	6
II. Thermometer Performance.....	11
III. Bottom Current Data at Station 89.....	41

LIST OF FIGURES

Figure	Page
1. Location chart of Kara Sea.....	3
2. Track of NORTHWIND.....	8
3. Ice Conditions in the Kara Sea.....	9
4. Station Locations.....	10
5. Physiographic Chart of the Kara Sea.....	21
6. FGR echograms of Ob-Yenisey Delta.....	23
7. FGR echograms of small leveed channels.....	24
8. Bottom Sediments.....	27
9. Profiles across the Novaya Zemlya Trough.....	28
10. Profiles across the Svyataya Anna and Voronin Troughs.....	30
11. Bottom Topography.....	31
12. Temperature - Salinity diagram showing water masses of the Kara Sea.....	38
13. Temperature - Salinity diagram (Cross section J-J').....	40
14. Temporal Changes at the entrance to Proliv Vilkitskogo.....	42
15. Temporal Changes in the Kara Sea.....	43
16. Profile of Dissolved Oxygen (Cross section J-J').....	46

LIST OF FIGURES (Continued)

Figure	Page
17. Profile of pH (Cross section J-J').....	46
18. Profile of Reactive Silicate (Cross section J-J').....	47
19. Profile of Reactive Phosphorus (Cross section J-J').....	47
20. Temperature - Salinity diagram (Cross section O-O').....	52

ABSTRACT

Movement of Atlantic Water into the Kara Sea is controlled by the bathymetry which funnels the inflow up three canyons along the eastern margin of the Svyataya Anna Trough. Mixing of the warm, saline Atlantic Water in these canyons with the considerable summer outflow of the Ob-Yenisey rivers results in the formation of Arctic Bottom Water and due to the presence and cooling by ice, in the formation of Arctic Surface Water. Both of these water masses then exit the Kara Sea as deep and shallow countercurrents to the incoming Atlantic Water. The northernmost canyon allows some Atlantic Water to exit the Kara Sea almost upon entrance, reducing the amount of heat and salt entering the Kara Sea.

The presence and extent of the bottom sediments reflect the path of the rivers across the Kara. Inflow of deep Atlantic Water tends to reduce this effect and results in scoured areas at the heads of the canyons, which are sites of turbulent mixing.

Ice is a major factor in the Kara Sea. It cools and dilutes the surrounding water. In the form of icebergs, it gouges paths through the soft, shallow, deltaic sediments and in the deeper areas, deposits ice rafted material.

THE KARA SEA:
GEOLOGIC STRUCTURE AND
WATER CHARACTERISTICS

FOREWORD

The Kara Sea is an epicontinental shelf sea on the northern border of Soviet Russia. The area is of interest to ocean scientists because of its influence on deep ocean water and, by controlling the formation of ice, on weather conditions in the Northern Hemisphere. Because of its isolation (Figure 1) and high cost of exploration, the Arctic has not received the attention devoted by U.S. oceanographers to the more temperate zones.

The first known survey of the Kara was made in 1594 by William Barents. Later, spurred by the urging of Peter the Great of Russia in the early 1700's, the Great Northern Expedition of 1733-43 succeeded in mapping the northern coast of Asia and Europe. Economic reasons, rather than scientific, were the primary motivation for these early explorations as attempts were made to find a water route over the top of Eurasia (Gordienko, 1961). In 1763, Mikhail Lomonosov wrote the first significant scientific work of this area, "Brief Account of Travels in the Northern Seas". The Swedish explorer, N.A.E. Nordenskjold, made the first passage from the Barents Sea to the Pacific Ocean in 1878 and established the Northeast Passage. Nordenskjold, who explored the Kara Sea in 1875 and 1876, published the first accurate chart of the area.

In 1893, the Norwegian oceanographer, Fridtjof Nansen, crossed

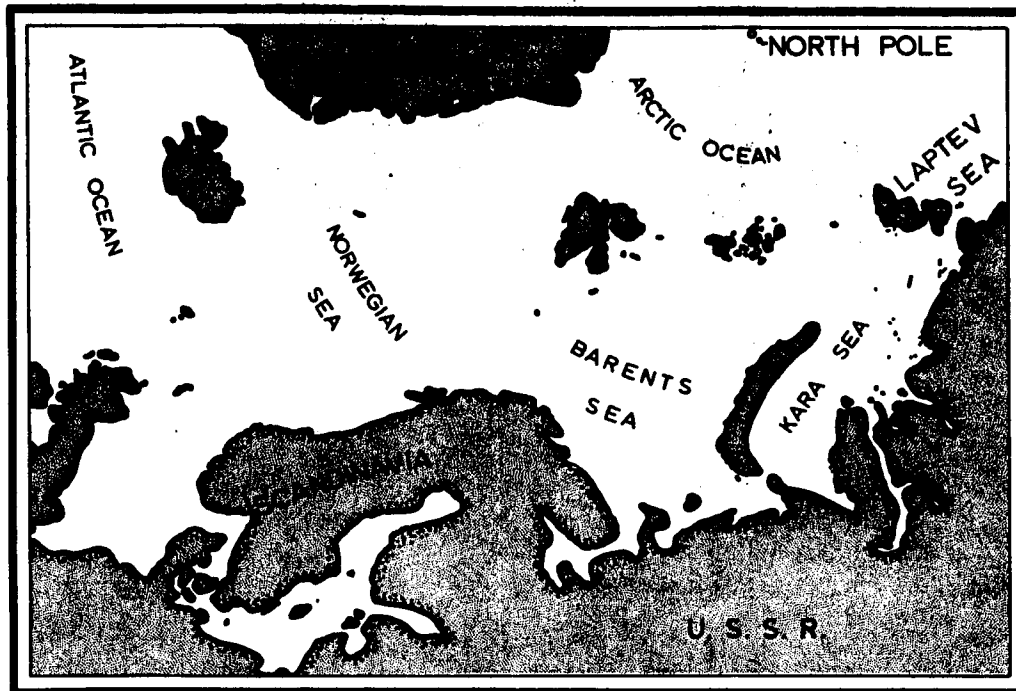


FIGURE 1. Chart Showing Relative Inaccessibility of Kara Sea

the Kara Sea in the historic voyage of the Fram (Nansen, 1902).

The U.S.S.R. has underway an extensive oceanographic program in the arctic peripheral seas; however, the data collected on these surveys are not readily available to western scientists.

The United States Navy through its Oceanographic Office has been conducting arctic exploration ranging from manned ice islands, aircraft overflights, and exploration by icebreaker, the last beginning in a systematic way in 1961. The Kara Sea survey, on which this work is based, was the final of the initial visits to a major epicontinental sea forming the margin of the Arctic Ocean. The author was Chief Scientist on this survey in the summer and fall of 1965 (Petrow, 1967). The significance of the Kara and other marginal seas, which incidentally occupy 36% of the aerial extent of the Arctic Ocean, is their effect on surface water conditions.

These shallow seas, while only containing 2% of the volume of water of the Arctic Ocean (Coachman and Aagaard, 1974), have an exaggerated influence due to their substantial input of freshwater in summer, which greatly influences the extent and thickness of the polar ice cap. The Kara Sea is the most productive of the marginal seas in volume of water contributed to the Arctic Ocean (Coachman and Aagaard, 1974).

INTRODUCTION

Objectives. The objectives of this study were to:

1. Characterize the various water masses in the Kara Sea, and examine mixing processes.
2. Delineate the physiographic provinces of the Kara Sea.
3. Relate and determine the causal relationship between the water mass dynamics and bottom bathymetry.
4. Determine the origin of small leveed channels common along the outer edge of the Ob-Yenisey delta.
5. Reexamine the formation of Arctic Surface Water which forms in the Kara Sea.
6. Examine the surface and subsurface sediment distribution and its relationship to the large rivers emptying into the Kara Sea.

This study focuses on the morphology of the present Kara Sea area and the continuing effect by the silt laden rivers, inflowing Atlantic water, various currents, and ice formation on the underlying form and structure of the bottom and subbottom. Data were obtained primarily from precision depth recorder records, and Nansen casts taken in the summer and fall of 1965.

Setting. The Kara Sea is a shallow sea enclosed by the Zemlya

Frantsa Iosifa, Severnaya Zemlya, and Novaya Zemlya island groups; the Russian mainland on the southeast; the Barents Sea on the west; and the Arctic Ocean on the north (Figure 1). The sea is approximately 1,300 km in length, has an area of 851,000 km², an average depth of 90 m, and a volume of 111,000 km³ (Andrew and Kravitz, 1974). The Kara Sea overlies a portion of the Asian continental shelf; consequently, in only three areas do depths exceed 200 meters.

Several major Siberian rivers empty into the Kara Sea (Table I). This outpouring of warm waters, which occurs mainly during

TABLE I. Siberian Rivers Emptying Into the Kara Sea and Vicinity (After L'vovich, 1953)

<u>RIVER</u>	<u>LENGTH (km)</u>	<u>Drainage Area (km²)</u>	<u>Annual Discharge (km³)</u>
TAYMYR	600	72,000	20
PYASINA	820	192,000	80
YENISEY	3,354	2,599,000	548
TAZ	779	108,000	47
PUR	256	67,000	29
OB	3,676	2,485,000	394
PECHORA	1,790	327,000	129

the summer months and amounts to approximately 1100 km³/yr, entrains and mixes with vastly more saline water to form a brackish water type that overlies colder and heavier water. According to Antonov (1958), 213,000 km³/yr flow into the Arctic Ocean from all sources. Eighty-three percent of this volume comes from the Atlantic Ocean as the West Spitsbergen Current flowing between Greenland and Spitsbergen. Continental Runoff constitutes less than one percent of the water entering the Arctic Ocean. Nevertheless, the small amount of Continental Runoff exerts far greater influence on the currents and Arctic Basin water masses than the volume of runoff would indicate.

Methodology. The approach used in this study was dictated by the fact that this was the first exploration of the Kara Sea by scientists from the United States. It therefore was deemed desirable to collect as much data as possible for a wide range of disciplines during the time available.

In addition to the oceanographic program aboard NORTHWIND, Dr. N. Ostenso, two graduate students, and one technician from the University of Wisconsin conducted a geomagnetic and gravity program (Vogt, 1968; Vogt and Ostenso, 1973).

Underway water sampling began on 18 July enroute from Copenhagen, Denmark to the Kara Sea. A temporary halt was called on 5 August and a damaged starboard shaft was replaced while the ship was drydocked in Newcastle, England. On 10 September, water sampling was resumed, and oceanographic stations were occupied from 12 September to 2 October. A track of the survey is presented in Figure 2.

Oceanographic operations in the Kara Sea were not hampered greatly by ice (Figure 3). Close ice, found along the east coast of Novaya Zemlya, apparently was due to prevailing winds. When NORTHWIND returned to the area following the inport period, almost all the ice had disappeared. Permanent arctic pack ice was not encountered until NORTHWIND had penetrated north of Severnaya Zemlya. The northernmost line of stations was taken in and just south of this pack. Along this line, grease ice and pancake ice were encountered, and at 80° E, the ice increased to close pack. However, the existence of polynyas still permitted oceanographic stations to be taken. Close pack also was found along the southeast

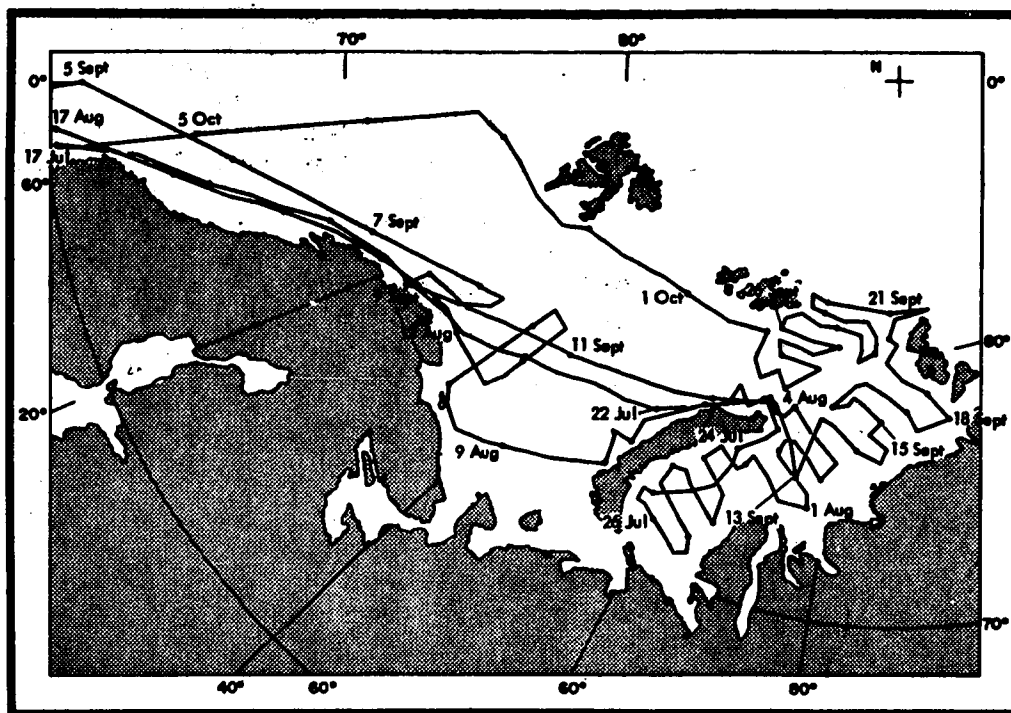


FIGURE 2. Track of NORTHWIND, July-October 1965

and southern coasts of Zemlya Frantsa Iosifa.

One hundred-sixty-three oceanographic Nansen stations were occupied in the Kara Sea and adjoining Barents Sea (Figure 4). Observations were made from the surface to the bottom at all stations, usually with a single cast of 13 or 14 Nansen bottles. The tin-lined Nansen bottles carried two and sometimes three protected thermometers and one unprotected thermometer. Due to the shallow water and the close proximity of ice, the wire angle of the Nansen cast usually was less than 5 degrees. On the shallow stations where an appreciable wire angle was encountered, depth calculations were made by multiplying the cosine of the wire angle by the length of wire out. Thermometers were allowed at least 6

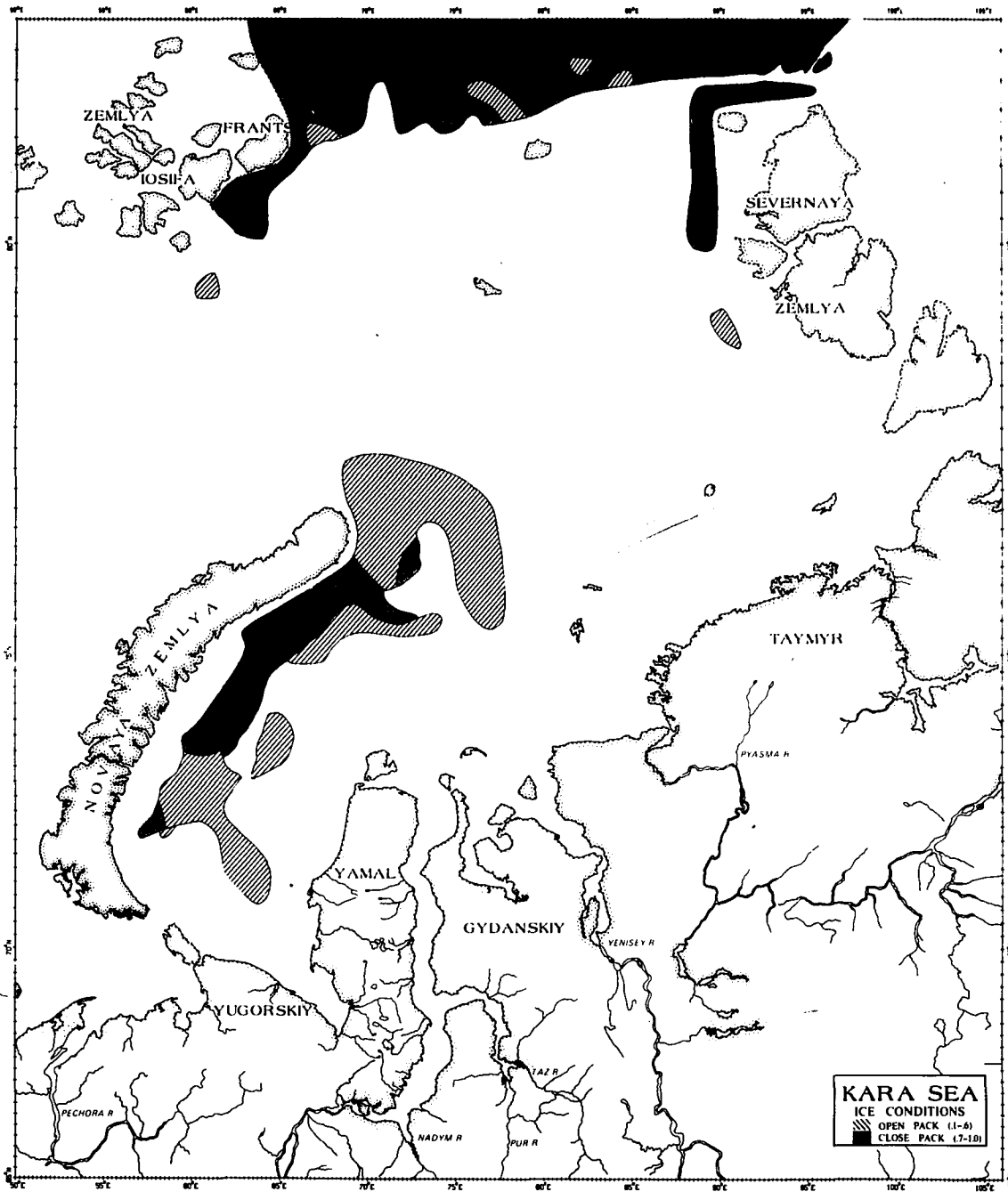


Figure 3. Ice conditions in the Kara Sea during July - October.

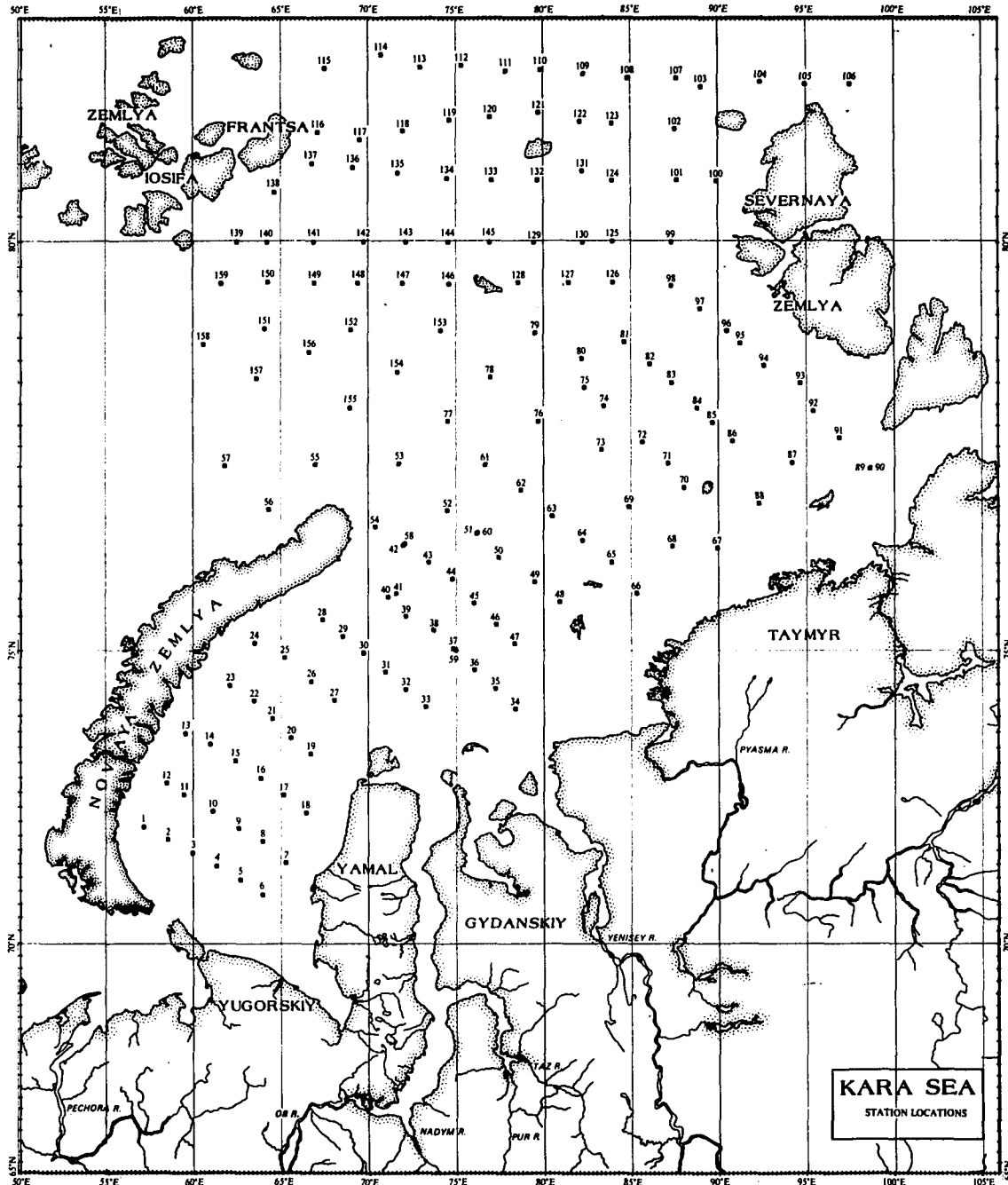


Figure 4. Station locations in the Kara Sea.

minutes to come to equilibrium before reversal. Approximately 88 percent of the paired thermometer readings agreed to within 0.02° C. Table II groups the temperature differences between paired thermometers and gives the number of readings in each group.

TABLE II. Thermometer Performance

0.00-0.02°C	0.03-0.04°C	One Thermometer Accepted	Greater than 0.04°C or a Malfunction
3,092	168	200	62

At the oceanographic stations, 1,814 temperature, salinity, dissolved oxygen, nitrogen, and pH observations were made.

Salinity samples were analyzed aboard ship using induction-type salinometers. Difficulties were encountered with the two salinometers, and salinity samples collected after station 57 were returned to NAVOCEANO for a second analysis. This check did not produce the anticipated results, and the best claim for this cruise is ± 0.10 ‰. However, with the marked variations of salinity with depth due to the large amounts of runoff from the Ob and Yenisey Rivers, the salinometer problems have not materially affected conclusions based on the survey.

Dissolved oxygen and nitrogen contents were measured using a modified Fisher Gas Partitioner equipped with an integrating recorder (Sullivan, 1963).

A Beckman Model 76 expanded scale pH meter was used for pH determinations.

Water samples were collected, frozen and later returned to

NAVOCEANO for reactive phosphorus and reactive silicate analyses, using the methods of Murphy and Riley (1962) and Strickland and Parsons (1965).

Bathythermograph lowerings were taken by ship's personnel using a mechanical BT.

Plankton tows were taken while drifting on station and were preserved in an aqueous solution of formaldehyde and returned to Dr. Neil Anderson of NAVOCEANO for analysis.

The continuous air sampling program consisted of mounting a pump on the flying bridge and drawing air through a filter. The filters were changed every 3 days and returned to Dr. J.H. Harley of the Health and Safety Laboratory, U.S. Atomic Energy Commission.

Twenty-five nannoplankton samples were collected for Dr. A. McIntyre of the Lamont-Doherty Geological Observatory for electron microscope analysis. Surface water samples initially were sieved through a wire mesh to remove all coarse material and then were pumped through a very fine filter.

Thirty-five 30-gallon water samples for gamma-radiation analysis were collected while the ship was underway. These samples were drawn through the ship's fire main system after first flushing the fire main for 30 minutes. In the deeper trench areas, the gamma-radiation samples were taken while the ship was lying-to using a Bodman bottle at 100-meter depth intervals. To indicate possible pretrips, a Nansen bottle was placed directly above the Bodman bottle, and salinities of the two samples were compared.

Six core samples collected for gamma-radiation analysis of

the surface layers were frozen immediately after they were collected.

The 95 Kullenberg gravity cores, averaging 1 to 2 meters in length and 5 centimeters in diameter, were collected in plastic (Tulox) liners, wrapped with Saran Wrap, and covered with a thick layer of wax. These cores were divided between the University of Wisconsin and NAVOCEANO. The cores, when opened at NAVOCEANO 3 to 4 months later, had suffered very little desiccation. They were analyzed for specific gravity, moisture content, organic carbonates, bulk density, porosity, lithology, and grain size (Andrew and Kravitz, 1974).

The 48 bottom grab samples were taken using either a Shipek grab or a weighted orange peel bucket sampler. These samples were divided between the University of Wisconsin and the Smithsonian Institution. The Smithsonian Institution samples were preserved with dilute alcohol and sealed in pint jars for foraminiferal examination (Stoll, 1978; Todd and Low, 1980).

Two current stations were taken in the Kara Sea. The first, while examining a shoal area, was of 4 hours duration. The second was taken for 24 hours to obtain information for a full tidal cycle. The current meter used was a Hydro Products Model 460 current speed sensor (Savonius rotor type) and Model 465A current direction sensor. Both sensors were connected to deck readout modules and Rustrak recorders.

A total of 20,000 km of bathymetric profiling was recorded along the entire track of the survey using an Alden Precision Graphic Recorder (PGR) Model 418. At half-hour intervals, the PGR record was annotated with the date and time.

Using a Giffit transceiver in conjunction with the PGR, continuous subbottom seismic reflection profiles were recorded along with the bathymetry for much of the track of the NORTHWIND. Bottom penetration was possible due to the variable pulse length of the transceiver and the shallow depths of the survey area.

Ship positioning was unusually accurate due to the installation of a Satellite Navigational System (SRN-9) designed by the Applied Physics Laboratory, Johns Hopkins University and used for the first time in the Arctic on this survey. The accuracy of this system was about 150 meters.

Oceanographic station data were checked, coded, and forwarded to the National Oceanographic Data Center (NODC). Machine computations produced sigma-t, dynamic depth and specific volume anomalies, and sound velocity values at observed and standard depths.

Appendix B, areal distributions of the parameters of temperature, salinity, silicate, oxygen, phosphorus and pH were computer drawn by a program which may briefly be described as a general purpose gridding algorithm for randomly spaced data. The program uses as input one set of triples $\{\phi_i, \lambda_i, a_{i,j}\}$, (i.e., for $i = 1, 2, \dots$, number of observations; j fixed) and generates a gridded representation of what is called a coefficient surface.

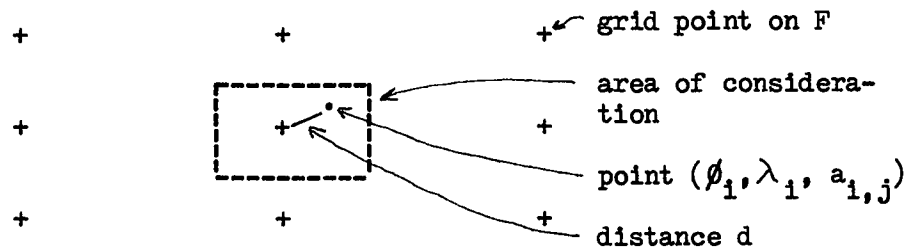
When a coefficient surface is prepared, a contoured plot of the field is produced and used for checking the integrity of the surface and the quality of the input data.

The gridding process is performed in the three sequential steps discussed below.

There are two grid definitions used in the process and they

are referred to as the final grid ($F(x,y)$) and the regional grid ($R(x,y)$). The final grid for this development has a 30-minute latitude grid interval and a 30-minute longitude grid interval and covers an ocean basin. The regional grid completely overlaps the final grid, extends beyond the boundaries of the final grid, and has a grid interval three times that of the final grid. Furthermore, grid points in the overlapping region of R lie at grid points of F .

The first operation assigns a grid-point value to each point on F which has values lying within $1/2$ an interval distance.



When there are several such points within the area of consideration, all values within $1/2$ grid interval are averaged. This operation is performed grid point by grid point, and F is left with values assigned to some points and not assigned others. The set of assigned grid point values are represented by $\{f_{i,j}\}$ and the unassigned set by $\{f'_{i,j}\}$ where the i,j represent the grid point location (each is some linear function of ϕ and λ), and f is the assigned value.

Regional grid development is concerned with providing an estimate of missing values $\{f_{i,j}\}$ which represent gaps in the final grid F . The process serves as a low pass two-dimensional filter and consists of four steps. First, a set of smoothed data points.

is generated by the application of a two-dimensional running mean operating of F . Second, a minimum curvature two-dimensional spline is computed using the smoothed data points. Third, the spline function is interpolated at each point on R . Fourth, successive applications of the one-dimensional spline, along grid rows and then columns (or vice versa), are used to interpolate R at every point on \bar{F} .

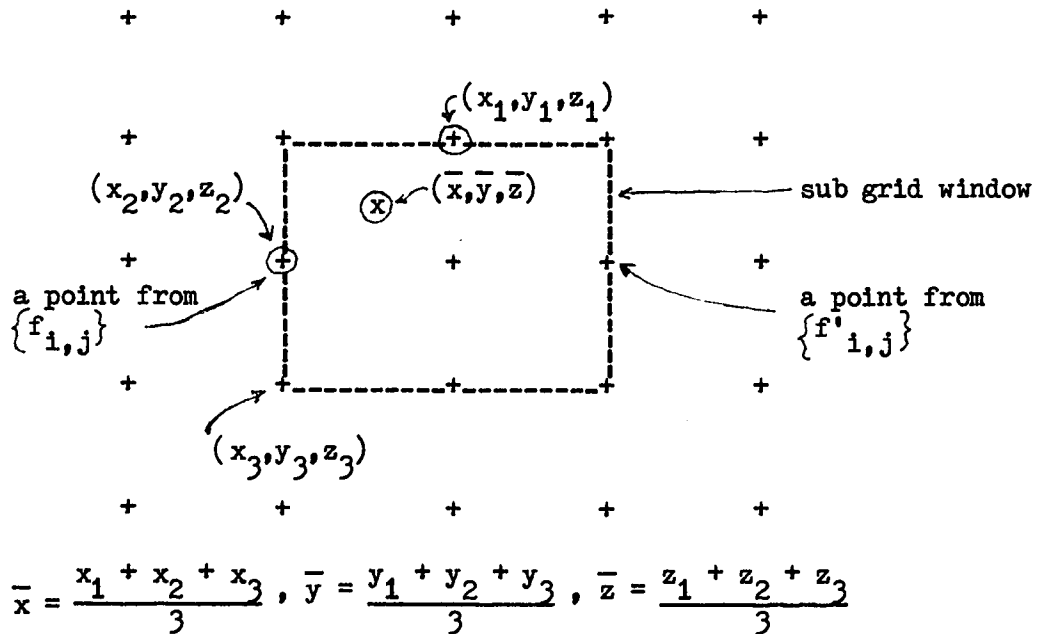
Now the two distinct data sets $\{f_{i,j}\}$ and the smoothed grid $\bar{F} = \{\bar{f}_{i,j}\}$ are used as input to the third and final analysis step.

This process involves combining $\{\bar{f}_{i,j}\}$ from the smoothing process with $\{f_{i,j}\}$ from the distance weighting process. An area of consideration is fixed to be a 3×3 subgrid centered at the grid point being evaluated. Each grid point in $\{f_{i,j}\}$ is assigned a weighted value based on the number of values from $\{f_{i,j}\}$ which lie within this area of consideration.

For example, the subgrid contains 9 points, 3 of which were from the set $\{f_{i,j}\}$, then the replacement value for \bar{f} at the point would be $3/9$ of f at the point plus $6/9$ of \bar{f} at the point. If all 9 values within the subgrid are from $\{f_{i,j}\}$, then the replacement $9/9 f$ at the point or simply, \bar{f} is totally replaced by f at the point. The primary purpose for using this weighting scheme is to provide for a smooth transition on the surface from areas defined by $\{f_{i,j}\}$ to areas defined only by $\{f_{i,j}\}$.

A smoothed data point $\{\bar{f}_{i,j}\}$ developed from a subset of $\{f_{i,j}\}$ on F is represented by the triple $(\bar{X}, \bar{Y}, \bar{Z})$ where \bar{X} is an average ϕ , \bar{Y} is an average λ , and \bar{Z} is an average coefficient surface value. These averages are computed from those data of the set $\{f_{i,j}\}$ which are located in an area of consideration, or subgrid window.

The size of this subgrid is independent of the definition of R. For the present operation, this subgrid is user set to be 3 X 3 grid points on the F grid. The nine grid points within the window are evaluated as illustrated:



The window is moved and evaluated one interval at a time, over the entire F grid. Each evaluation results in a smoothed data point for the next step.

GEOLOGIC STRUCTURE

Literature Review. The Kara Sea is an epicontinental sea, a part of the Arctic Ocean, which overlies the Eurasian Continental Shelf. It is bordered on the north by a line drawn between the island groups of Zemlya Frantsa Iosifa and Severnaya Zemlya; on the east and south by the Eurasian coast; on the west by the islands of Novaya Zemlya, and a line connecting Novaya Zemlya and Zemlya Frantsa Iosifa. The northern limit is approximately the edge of the continental shelf bordering the Arctic Ocean. The area of the Kara Sea is $851,000 \text{ km}^2$ with a volume of $111,000 \text{ km}^3$ (Andrew and Kravitz, 1974). The Kara Sea shelf has a heterogeneous basement consisting of Precambrian and Paleozoic structures (Meyerhoff and Meyerhoff, 1973; Ostenso, 1974). Upon this base repeated episodes of terrestrial and marine sedimentation, along with magmatic intrusions, have taken place (Bondarev, et al. 1973; Ostenso, 1974).

Regionally the structure of the Kara Shelf has been determined by events outside its periphery, i.e., the evolution of the Arctic Ocean basin (Harland, 1973). Until late Paleozoic, Eurasia consisted of two separate continental fragments - the Russian and Siberian platforms (Churgin, 1973). These fragments converged during the middle Paleozoic and in the Permian or Triassic formed the Uralides (Hamilton, 1970; Ostenso and Wold, 1973). The islands of Novaya Zemlya are a northern continuation of this fold belt, and they

received sedimentation throughout Paleozoic time (Harland, 1973 ; Meyerhoff, 1973). The Arctic Basin is divided by the Lomonosov Ridge into the Canada Basin and the Eurasian Basin (Ostenso, 1974). The Eurasian Basin, which borders the Kara Shelf, is believed to be younger than the Canadian due to the fact that it truncates Paleozoic fold belts such as the Urals which lie on its periphery (Churkin, 1973). It is underlain by oceanic crust and apparently formed in connection with sea-floor spreading from Gakkel Ridge, a continuation of the Mid-Atlantic Ridge (Churkin, 1973; Vogt and Avery, 1973). Undeformed Cenozoic and, in places, Mesozoic deposits rimming the Eurasian Basin, e.g., flat-lying Mesozoic strata found on Zemlya Frantsa Iosifa and on Severnaya Zemlya (Churkin, 1973) indicate that no major movement has occurred between the floor of the Arctic Ocean basin and its continental margins since at least Early Cretaceous time. The floor of the Kara Sea and many of the islands show evidence of past glaciation in ice eroded terraces. Novaya Zemlya and the Taymyr-Severnaya Zemlya region were principal centers of glaciation, as they are today, which spread over the western Siberian plain (Saks, 1948; Saks and Strelkov, 1961). Conflicting evidence of sea level fluctuations in the Kara Sea are emergent features along the shores of Novaya Zemlya, contrasted with the ability to trace the channels of the Ob and Yenisey Rivers out to a depth of 100 meters (Saks, 1948). Magnetic basement is found at depth in the southwestern Kara Sea but shoals northeast of a line connecting Northern Novaya Zemlya with the Yenisey Estuary (Vogt and Ostenso, 1973). This further supports vertical movement as indicated by surface features. The Kara Shelf is incised by

the Svyataya Anna and Voronin Troughs (Figure 5), both of which have indications of glacial origin (Johnson and Milligan, 1967), but possibly formed by major faulting (Gakkel and Dibner, 1967) modified by glacial action. The East Novaya Zemlya Trough appears in form to resemble a deep-sea trench (Johnson and Milligan, 1967) parallel to and convex towards Novaya Zemlya. A glacial erosion origin (Johnson and Milligan, 1967) is strongly favored for this trough on the basis of its geographic location and similarity to other high latitude troughs, although as with other features in the Kara Basin, it has been modified by later erosion and deposition.

Klenova (1936) first discussed sediment distribution in the southern Kara Sea. She noted that cyclonic rotation of the surface water in the southern Kara Sea was reflected in sediment texture with the finer material accumulating in shallower areas. The sediments tended to be silty clays, muds and glacially derived silts. Turner (1973) on the basis of sediment core samples from the Kara Sea found an increase in concentration of nondetrital iron in surface sediments toward the Siberian mainland consistent with river discharge as the source. He noted that distribution of the nondetrital iron and manganese appears to be controlled by postdepositional processes, rather than by primary depositional processes.

Andrew and Kravitz (1974) examined cores from the NORTHWIND survey and on the basis of analyses for grain size, organic-carbon content, water content, sand content, and clay mineral ratios postulated a north-flowing bottom current on the eastern side of the Svyataya Anna Trough. In the Voronin Trough, they felt intermittent

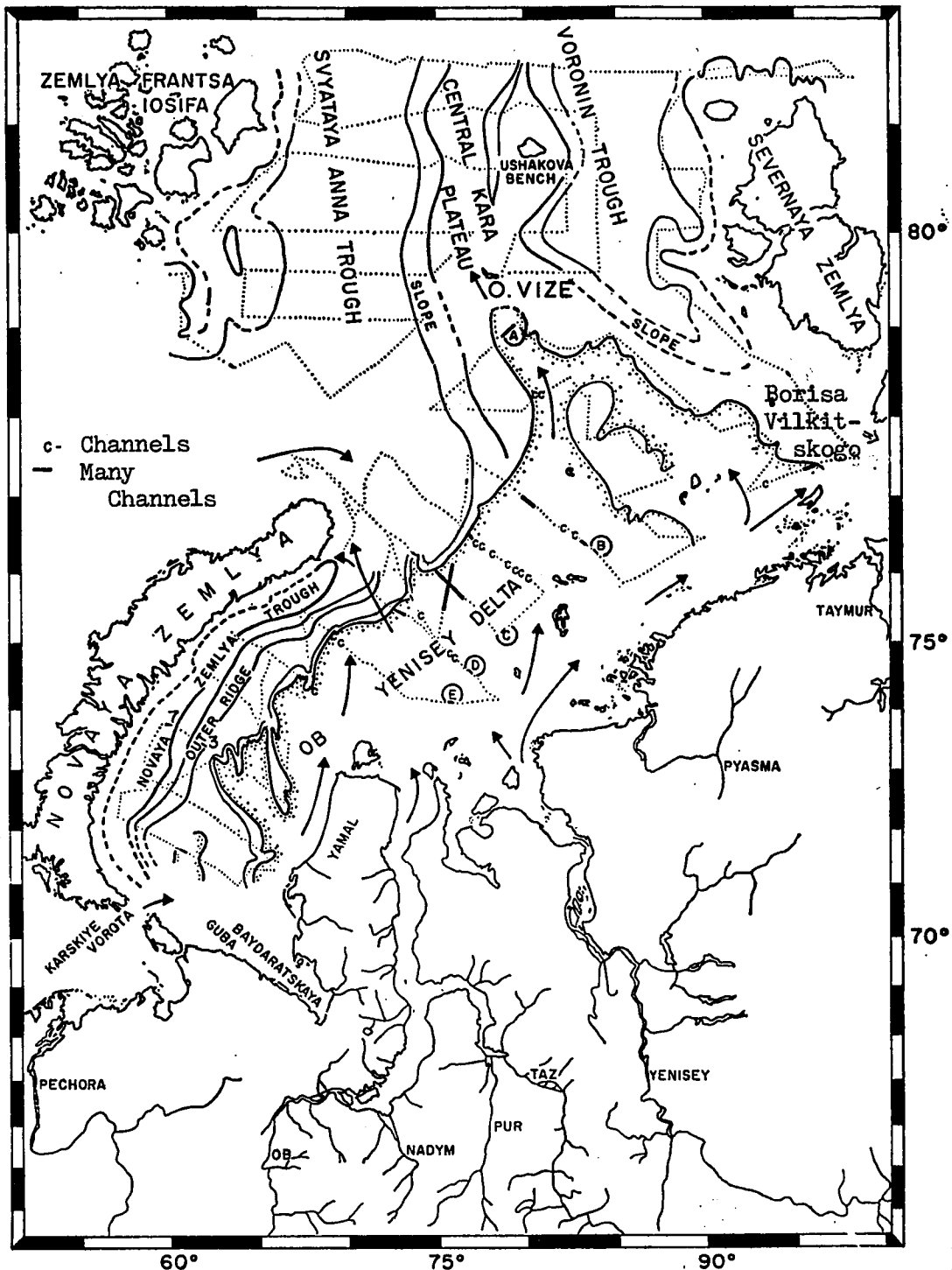


Figure 5. Physiographic provinces of the Kara Sea. A heavy bar indicates a region where many small channels are found; c = a solitary small channel. Numbers refer to profiles on Figure 7. Letters refer to profiles on Figure 8. Arrows = circulation pattern. Dotted lines indicate ship's track.

bottom currents best explained the dispersal patterns observed there.

Discussion of Data. The major physiographic provinces in the Kara Sea (Figure 5) were delineated by the study of precision echograms and exaggerated profiles of soundings using the method employed by Heezen et al (1959). By this means the Ob-Yenisey Delta is clearly defined as is the East Novaya Zemlya Trough, the Svyataya Anna Trough, the Voronin Trough, and the Central Kara Plateau lying between the Svyataya Anna and Voronin Troughs.

The Ob-Yenisey Delta is composed of flat-lying, shallow sediments resulting from the coalescence of deltaic fans from the Ob and Yenisey, along with other rivers (Figure 6). Saks (cited in Kulikov, 1961) estimated a rate of sedimentation for the delta at 30-100 cm per thousand years. It was not possible to discern a subbottom layer in these deltaic sediments, and it is believed that this is due to their thickness and homogeneity. In contrast, sedimentation rates, based on both radium concentrations and clastic inputs (Yermolayev, 1948) for the deeper areas of the Kara Sea range from 4 to 6 cm per thousand years. In the southernmost stations, it is believed (Nansen, 1902), and recent studies confirm it (Milligan, 1969; Garcia, 1973), that the Pechora River has contributed a considerable amount of sediment to this area.

Deltaic channels are an interesting feature common along the outer edge of the delta (Figure 6 and 7). The bottom of the channels average 20-80 m in width with levees that range from 1 to 8 m above the adjacent sea floor. The channels are shallow features and, excluding the leveed sides, range to 8 m below the sea floor. A previous examination of the channels by Johnson and

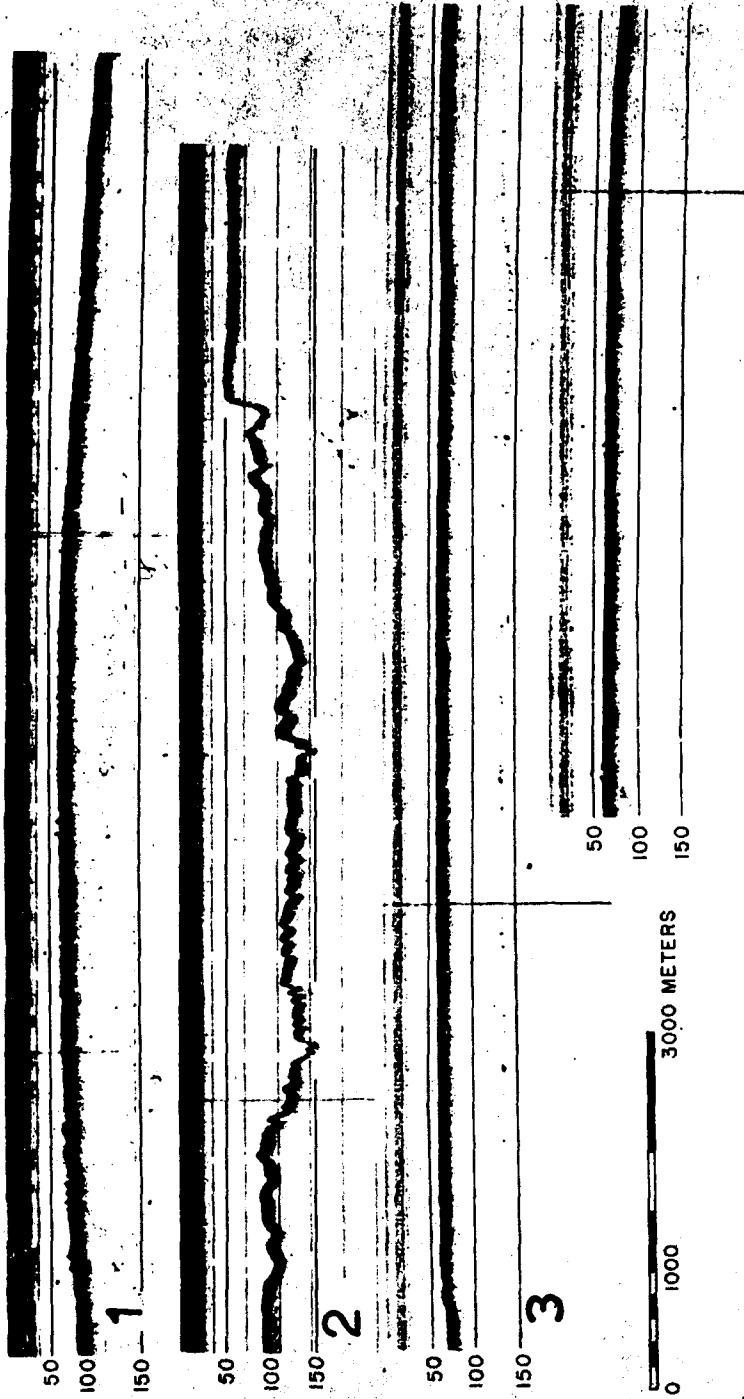


FIGURE 6. Three sections of PGR echograms with channels. Profile 1: Many small channels on the outer portion of the delta. Profile 2: Outer edge of the delta. Note typical hummocky relief just to the seaward of the very smooth deltaic seafloor. Profile 3: Pechora River delta with two small channels. All profiles are indexed on Figure 1 and have west on the left.

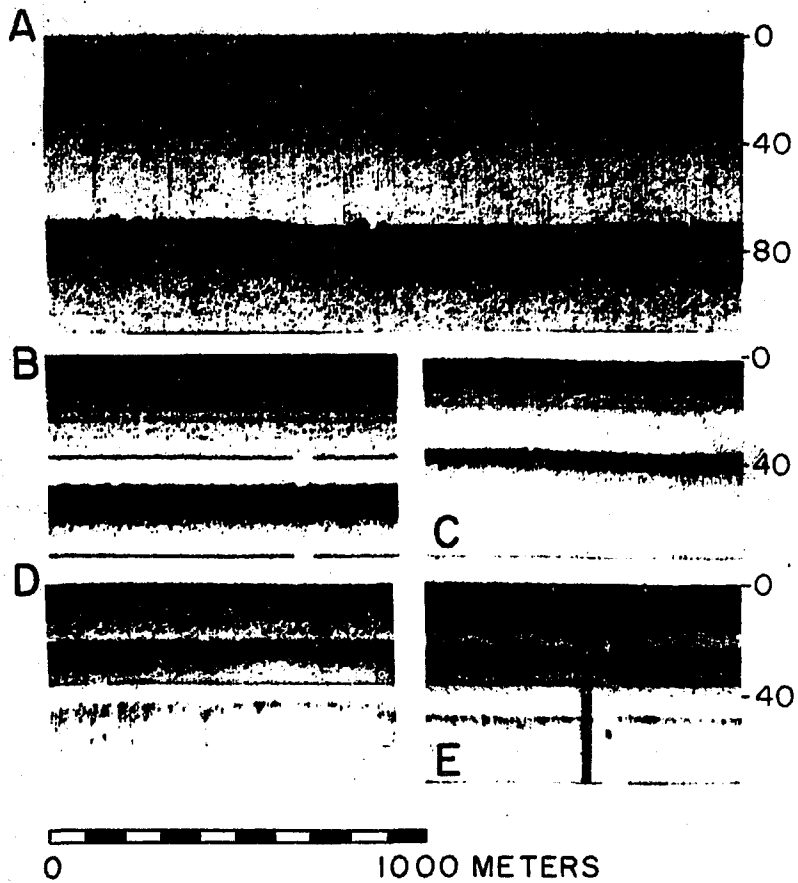


FIGURE 7. Five sections of PGR echograms showing small solitary channels. These sections are indexed on Figure 6. Note the variation in penetration in profiles C and D.

Milligan (1967) proposed various origins:

1. The channels were relicts of a lower sea level.

This would seem to contradict the evidence of the emergent shore line visible on Novaya Zemlya (Zenkovitch, et al., 1960) although it is supported by evidence that the rivers in western Siberia appear to be "entrenched" rather than drowned (Lazukov, 1964). This does not explain why the channels are found exclusively on the edge of the delta, nor why they do not appear to be sites of deposition.

2. The channels were cut by turbidity currents. It is certainly true that the spring break-up of the ice in the rivers causes flooding which would entrain salt water which had built up in the estuaries of the Ob and Yenisey during the winter low river flow. This would be further enriched with sediments, from the Ob River which has in excess of 13 million tons, and from the Yenisey which has a sediment load of 15 million tons (L'vovich, 1953).

Two problems arise with this, first the channels seem too small to carry this flow, and second, the channels should be better developed than they are near the river mouths.

3. A third consideration was that the submarine channels are small estuaries providing egress locally for saline water.

An estuarine circulation pattern must provide a subsurface inflow of saline water to maintain the salt balance with the outflow of freshwater which will have an admixture of saline water with it (Coachman and Barnes, 1961).

4. A simpler explanation now seems to be that the leveed channels are gouges made by icebergs as they scrape over the bottom.

This action has been observed and described by Canadian divers (MacInnis, 1970) "their movement is hardly noticeable, but the paths they leave look like a giant plowshare had been there". This action has also been observed from U.S. Navy submarines (personal communication by Vice Admiral E.W. Wilkinson, USN Ret.). This would explain the great number of channels on the leading edge of the delta, as well as their unusual leveed sides. It also should be noted that Severnaya Zemlya is the greatest producer of icebergs in the Soviet Arctic, and Novaya Zemlya also calves icebergs from its glaciated area. Finally, a great number of icebergs 30-60 m in height along with ice floes and ice ridges were observed while the NORTHWIND was on survey in the Kara Sea.

Outward from the delta, soft sediments overly the harder, more uneven bottom. This is particularly evident in the area between the Yamal Peninsula and the islands of Novaya Zemlya, where discontinuous subbottom reflectors are recorded from the delta to the westernmost edge of the survey area (Figure 8). There is a sharp break from the Ob-Yenisey Delta to the hummocky reliefs just beyond (Figure 6, Profile 2). Generally, the shelf beyond the delta is smooth and rolling, due in part to the mantling effect by suspended river sediments. Rough bottom is not uncommon, but can be explained as ridge areas showing through the overlying sediments.

The East Novaya Zemlya Trough lies parallel to and convex towards Novaya Zemlya. The floor is 20-40 km wide at the 300 m isobath. The trough averages 300-400 m in depth (Kulikov, 1961) and the NORTHWIND observed 430 maximum at $74^{\circ}40'$ N. The floor is smooth with undulation (Figure 9) and is overlain with generally con-

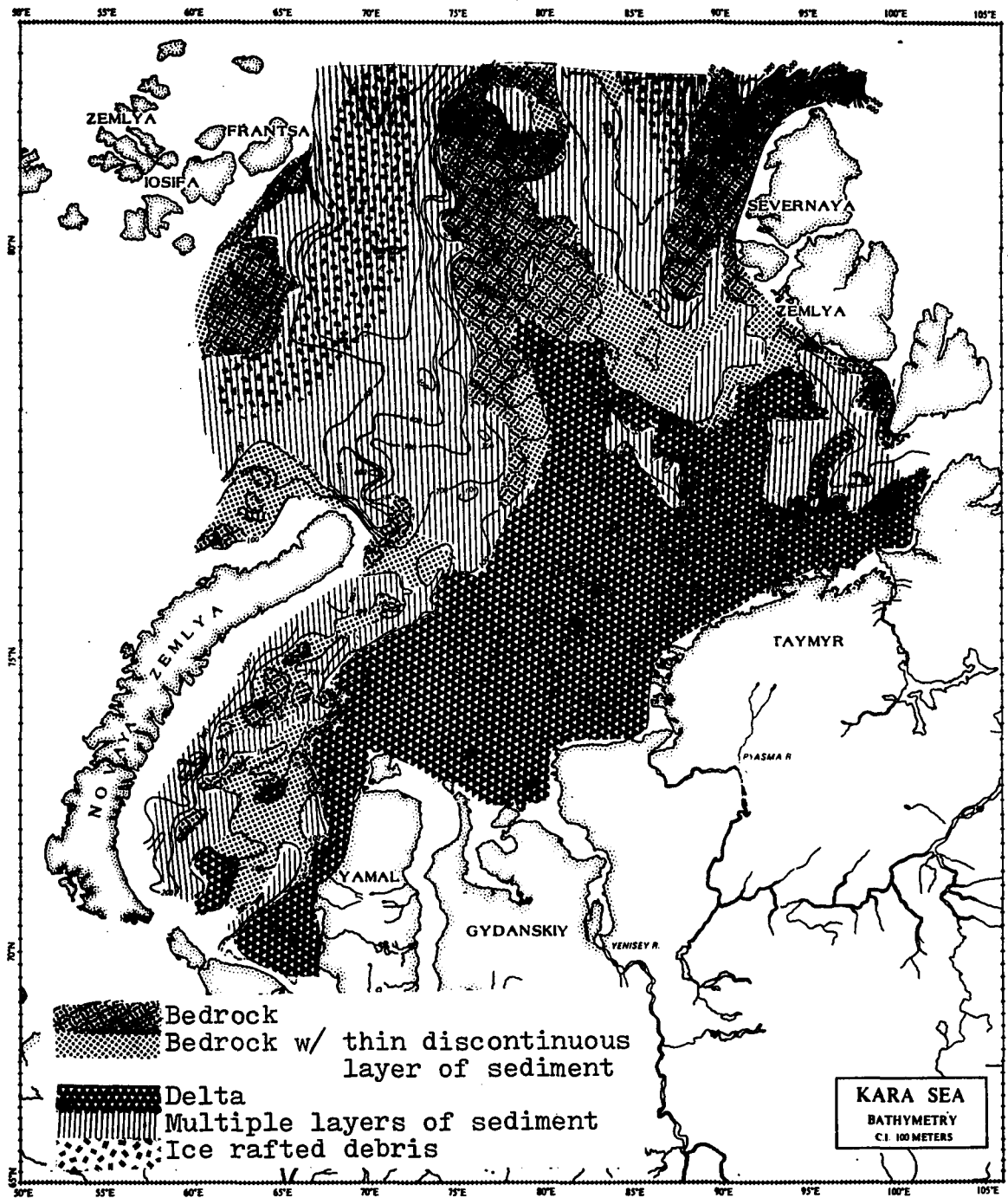


Figure 8. Bottom sediments

tinuous subbottom reflectors. Severe ice conditions in the lee of Novaya Zemlya did not allow an examination of the western edge of the trough. The eastern edge slopes 1:80 with the northern profiles having a gentler gradient. A probable outer ridge is located between $72^{\circ}30'$ N and 75° N (Figure 9, Profiles 4, 5, and 7). It is characterized by rough topography with probable rock outcrops. The trough shoals to 50 m in the northern end, with bedrock exposed between 100-200 m.

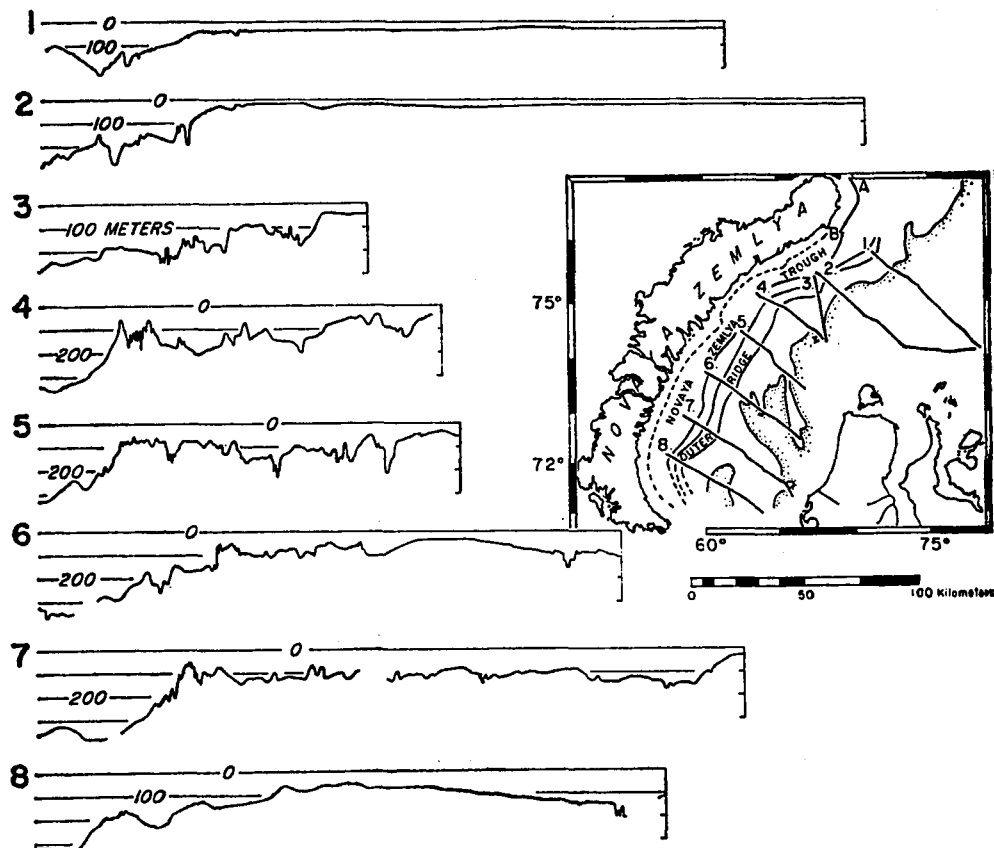


Figure 9. Eight transverse profiles at a vertical exaggeration of 100:1 across the Novaya Zemlya Trough.

The Svyataya Anna Trough separates the Central Kara Plateau from Zemlya Frantsa Iosifa. It is 400 km long and 150 to 200 km wide in the northern, deeper end. It opens to the south and west and deepens to 600 m off the northern tip of Novaya Zemlya. The floor is generally broad and flat with undulations. It is blanketed by a thin veneer of terrigenous sediments deposited by the Ob and Yenisey rivers (Figure 8). Along the eastern margin and in the deep area off Novaya Zemlya it is a site of more active deposition. The maximum water depth measured by the NORTHWIND 636 m along the northern edge of the trough is consistent with the figure of 600 m as reported in the literature (Kulikov, 1961). Slopes along the eastern margin measured 1:20 to 1:100, while slopes tended to be greater than 1:90 in the western area adjacent to Zemlya Frantsa Iosifa. Good evidence of slumps and creeps were present along those slopes.

The Voronin Trough separates the Central Kara Plateau from Severnaya Zemlya. It is 270 km long and 100 km wide. It also opens to the north with depths ranging from 400 m in the north to 200 m in the south. The floor of the trough is smooth with undulations, similar to the Svyataya Anna Trough, and covered in large part by thin, discontinuous layers of sediments as shown by the presence of a subbottom reflector over much of the area (Figure 8). The slope on the east is gentle, 1:100, and the western slope has an even gentler gradient.

The Central Kara Plateau lies between the Svyataya and Voronin Troughs (Figure 10). Two small islands are present on the plateau, of which the southernmost and smaller, O. Vize, consists of lower

Cretaceous strata. The northern island, Ushakova is completely ice covered. Although the southern end of the plateau is overlapped

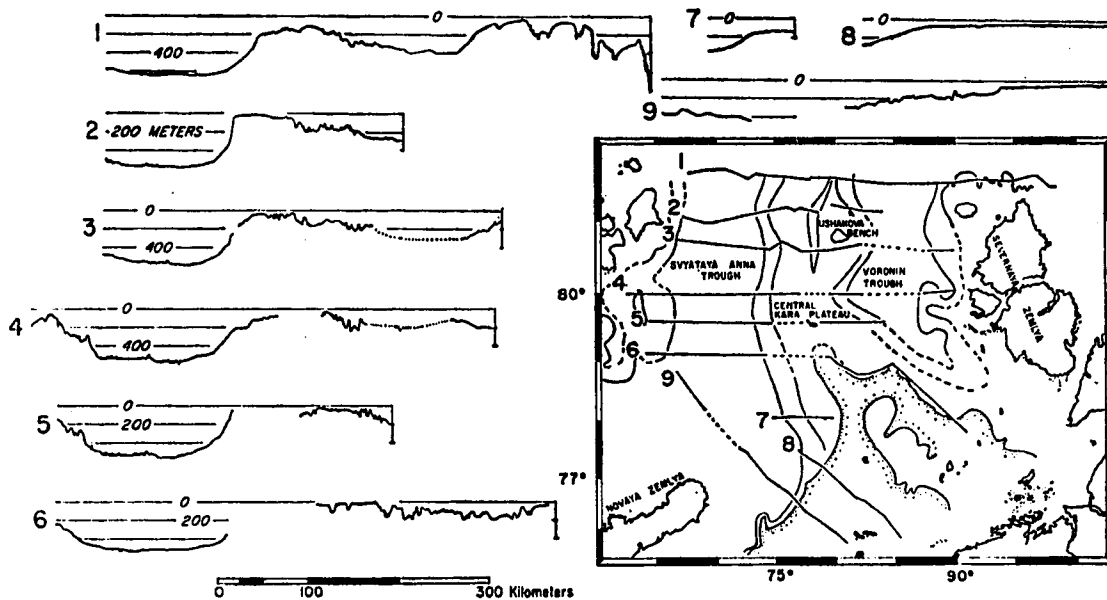


Figure 10. Nine transverse profiles at a vertical exaggeration of 100:1 across Svyataya Anna Trough, the Central Kara Plateau and Voronin Trough.

by the extension of the Ob-Yenisey Delta, the rough, rocky relief of the Central Kara Plateau indicates it is not simply an extension of the Ob-Yenisey Delta. The plateau core is assumed to be Proterozoic to Paleozoic with a veneer of Jurassic to Cretaceous sediments (Johnson and Milligan, 1967; Vogt and Ostenso, 1973; Meyerhoff and Meyerhoff, 1973; Ostenso, 1974). The bottom topography (Figure 11) indicates three canyons (Figures A-11, A-18, A-23) along the eastern margin of the Svyataya Anna Trough which offer preferential ingress for deep Atlantic Water entering the

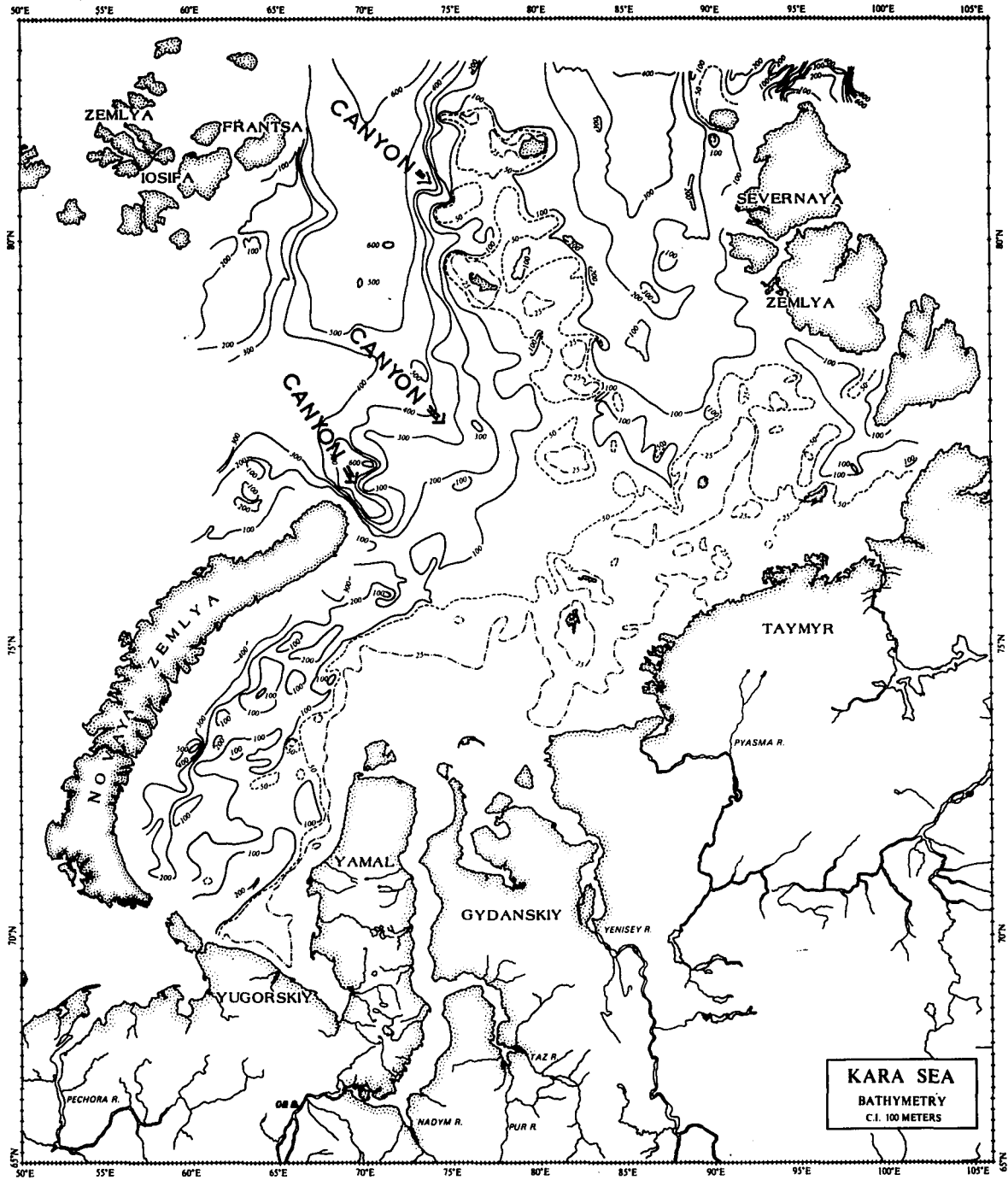


Figure 11. Bottom topography in the Kara Sea.

Kara Sea.

Conclusions. The use of precision echograms and exaggerated profiles of soundings allowed the physiographic provinces of the Kara Sea to be delineated. The extent of dispersal of sediments as shown (Figure 8) indicates the Ob-Yenisey Delta is building towards the Central Kara Plateau, but as yet has not covered the Pretertiary core. The path of the river runoff across the Kara Sea is clearly reflected in the underlying sediments. The inflow of deep Atlantic Water is marked by a lack of sedimentation where the canyon heads (Figure 11) incise the Svyataya Anna Trough. The Svyataya Anna Trough is being mantled by sediments primarily along the western side of the Central Kara Plateau. The Voronin Trough shows some effect of this along the eastern side of the Central Kara Plateau. The northern portion of the Novaya Zemlya Trough is a site of deposition for part of the flow from the Ob-Yenisey rivers which cut directly across towards the northern island of Novaya Zemlya.

The small, leveed channels found along the margin on the Ob-Yenisey Delta are almost beyond doubt the result of large icebergs slowly gouging their way through the soft sediment with the push of wind and current.

Subbottom penetration (Figure 8) along with core data (Andrew and Kravitz, 1974) supports the bathymetric data (Figure 11) in delineating the area of sediment influx, primarily from the Ob-Yenisey River systems. However, the deltaic sediments were too homogeneous and too thick for the Giffit transceiver to distinguish between thin bedded, coarse and fine bottom sediments. The southern Kara Sea between Novaya Zemlya and the mainland is being covered

with a thick veneer of sediment. The Svyataya Anna Trough has what appears to be soft, thick, homogeneous sediments over much of its central area. This overlies and smooths a swale type basement (Johnson and Milligan, 1967). The Voronin Trough has a thin and discontinuous cover indicating the flow of material is more to the west of the Central Kara Plateau.

Ice rafting debris was very evident (Figure 8) in the sediments of the central Svyataya Anna Trough and extended into the Barents Sea. This would seem to indicate that icebergs and floes are melting in this area due, in part, to the rising, warm Atlantic Water (Ostenso, 1974).

WATER CHARACTERISTICS

Literature Review. The Kara Sea is a shallow epicontinental sea which borders on and is a part of the Arctic Ocean. It is the second largest of the peripheral shelf seas of the Arctic. It derives its importance from the fact that its major rivers, the Ob and Yenisey, along with the Pechora and Pyasina contribute $42,000 \text{ m}^3$ per second, about one-half of the $85,000 \text{ m}^3$ per second river discharge which enters the Arctic Ocean (Coachman and Aagaard, 1974). Since the area is in equilibrium, it must receive an inflow from outside its basin, i.e., inflow of deep Atlantic Water (Coachman and Aagaard, 1974; Hanzlick and Aagaard, 1980). Micklin (1981) estimates the continental runoff into the Kara Sea at $1350 \text{ km}^3/\text{yr}$, and the inflow of deep Atlantic Water to be $19,534 \text{ km}^3/\text{yr}$ or 14 times the volume of the freshwater. This Atlantic Water brought in through the deep Svyataya Anna Trough and, to a lesser extent, through the Voronin Trough warms the overlying cold water of the Kara Sea and has produced a semipermanent polynya (Eskin, 1960) which is located just northwest of Ostrov Vizé on the eastern side of the Svyataya Anna Trough. This was an area of abnormally high phytoplankton biomass during the 1934 Sedov Expedition (Zenkevitch, 1963) and showed abnormally high dissolved silicate readings during the NORTHWIND survey, thirty years later. The Svyataya Anna Trough has been proposed (Coachman and Barnes, 1962; Micklin, 1981) to be the site

of significant transformation of Atlantic Water with an associated vertical heat flux.

The estimated mean annual discharge of the Ob and Yenisey rivers into the Kara Sea is $35,000 \text{ m}^3/\text{sec}$ or $1100 \text{ km}^3/\text{yr}$, more than one-half of which occurs during May-July (Hanzlick and Aagaard, 1980). They calculated the freshwater fraction for the Kara Sea based on the reference salinity of 34.5 ‰ to be a 3.5 m thickness of freshwater over the entire Kara Sea, which would represent 2.5 years of river discharge, a residence time not appreciably different from other adjacent areas of the Arctic Ocean (Aagaard and Coachman, 1975). It seems then, that there is a considerable buffer of freshwater in the Kara Sea, which makes for semipermanent, long-term water conditions.

High dissolved silica content is also characteristic of the river discharge to the Kara Sea, and has been used to trace the runoff of freshwater (Shpaikher and Rusanov, 1962).

The flow of freshwater from the rivers extends from the mouths of the Ob and Yenisey to the northern end of Novaya Zemlya; north over the Central Kara Plateau; and northeast along the coast of Soviet Russia. The Pyasina River contributes to this movement in building the shallow Ob-Yenisey delta northeastward along the Taymyr Peninsula coastline. The Pechora River enters the Kara Sea through Proliv Karaskiye Vorota as an offshoot of the Pechora Current (Novitskiy, 1961). The 1967 EASTWIND survey (Garcia, 1973) found "a tongue of warm water ... protruding into the southernmost line of stations in the Southern Kara Sea."

The influx of Atlantic Water into the Kara Sea has been

postulated since the time of Nansen (1902). Ice maps published weekly by the Fleet Weather Facility, Washington, D.C. indicate the area northeastward of Novaya Zemlya is an area with minimum ice thickness in the winter, and last to freeze in the fall. This is due to the relatively warm Atlantic Water rising and shoaling as it moves up the Svyataya Anna Trough entering the Kara Sea as a counter-current to the movement of river water out into the Arctic Ocean. Since the Kara Sea rivers are the main constituent of river water entering the Arctic Basin, it would seem to follow that the Kara Sea would be the site of the largest inflow of Atlantic Water. The Kara Sea and particularly the Svyataya Anna Trough area must be the largest mixing basin for Atlantic Water and river runoff in the Arctic Ocean. Hanzlick and Aagaard (1980) noted that 85% of the heat lost by the rising Atlantic Water was over the Svyataya Anna Trough.

Nevertheless, the Kara Sea is an area of significant ice formation, both as sea ice and calving from the adjoining glaciated areas. The changing ice cover was very evident during the NORTHWIND survey (Figure 3) and the ice cover during the summer months July-September is appreciably less than the almost total coverage afforded during the arctic winter. It has been estimated (Hanzlick and Aagaard, 1980) that the mean average river runoff would produce a layer of freshwater about 1.3 m thick if spread uniformly over the entire Kara Sea. Estimates of the average thickness of ice formed in the Kara each year are similar, about 1.5 m (Zubov, 1945). This ice, if annually exported, would balance the annual river runoff. However, the presence of Atlantic Water brought into

the Kara Sea through the Svyataya Anna and Voronin Troughs warms and decreases the annual formation of ice by 55 to 94 cm, depending on the year. Micklin (1981), based on Russian data, estimated the export of fall and winter ice as 240 km^3 or 21% of the ice formed or brought into the Kara Sea. The summer ice melt he estimated as 930 km^3 or 79% of the yearly ice production. Hanzlick and Aagaard (1980) have suggested, however, that estimates of heat flux over the Svyataya Anna Trough may be too high, based on examination of NORTHWIND data, which suggests a bifurcation of the Atlantic Water as it enters the Kara Sea. They believe bathymetric steering along the 600 m isobath causes a significant portion of the Atlantic Water to exit the Kara Sea almost immediately. This paper allows a reexamination of this thesis employing a different interpretation of the data.

Discussion of Data. Based on examination of data collected on the NORTHWIND survey there are six major water masses that either originate in or enter the Kara Sea from adjacent areas. These water masses are seen on T-S diagrams (Figure 12). The near vertical sigma-t lines on these T-S diagrams demonstrate that density of most Kara Sea waters is controlled principally by salinity.

The six water masses are as follows:

1. Continental Runoff. Relatively warm, freshwater that originates from the Ob and Yenisey rivers. This water was found at station 36 from the surface to 10 meters.

2. Atlantic Water. Relatively warm, saline water entering the Kara Sea through:

- (a) The Barents Sea between Novaya Zemlya and

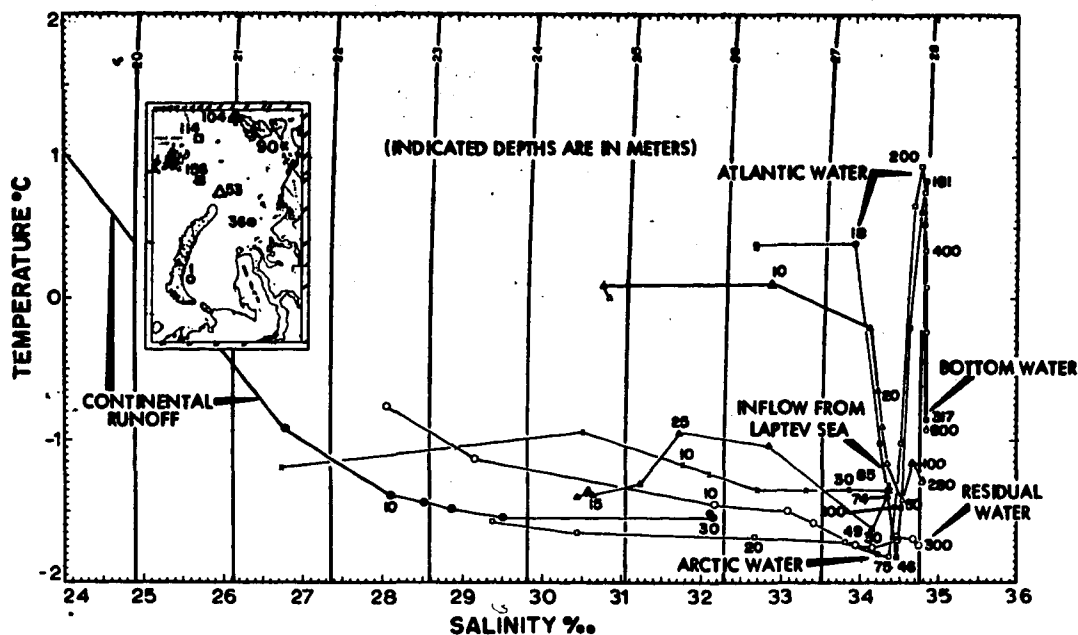


FIGURE 12. Temperature-Salinity Curves for Selected Stations

Zemlya Frantsa Iosifa. This water was observed at stations 53 and 156 and had a temperature of approximately 0°C and a salinity of 34°‰ at depths of 15 and 18 meters, respectively.

(b) The two deep trenches between Zemlya Frantsa Iosifa and Severnaya Zemlya. This water has a temperature of approximately 1°C and a salinity of 34.8°‰ and was observed at a depth of 200 meters at station 114 and 181 meters at station 156.

(c) The straits in the lower Kara Sea. A minor inflow of a less saline, colder Atlantic Water. (This water was noted by Nansen (1902).) Atlantic Water flowing through the straits in the lower Kara Sea was evidenced by water warmer than 0°C in the southernmost line of stations.

3. Arctic Surface Water. A salinity of 33.5 to 34.5 ‰ and a temperature of less than -1.5° C. This water mass is well developed at a depth of 50 to 75 meters in a number of areas, e.g., stations 114, 1, and 156.

4. Residual Water. Cold, highly saline, dense water found in the isolated deeps of the East Novaya Zemlya Trough (200 to 300 meters at station 1).

5. Water entering from the Laptev Sea. Below 20 meters at stations 89 and 90. This water had a temperature range of -1.2 to -1.4° C, and a salinity of 32.7 to 34.4 ‰.

6. Arctic Bottom Water. The densest of the water masses found in the Kara Sea with salinities of 34.8 ‰ and temperatures approaching -1° C. This water mass moves down the slopes of the trenches which incise the continental slope. Arctic Bottom Water was observed at stations 114 and 156 at depths of 600 and 317 meters, respectively.

Station 156 (Figure 12) shows diluted Continental Runoff at the surface, cold Arctic Surface Water at 46 m, relatively warm, rising Atlantic Water at 181 m, and Arctic Bottom Water at 317 m. Station 156 also shows that simply mixing surface water and the Arctic Water at 46 m does not form modified Atlantic Water at 18 m.

A section taken along the axis of the Svyataya Anna Trough, (Figure A-11) shows these water masses. Using the 0° C isotherm as the boundary of the Atlantic Water, the slope of this rising water mass parallels the slope of the bottom. The cold water mass found at a depth of 50-75 m is the Polar Water described by Nansen (1902), or in more recent terminology, Arctic Surface Water described by

Coachman and Barnes (1962). Water from the Ob and Yenisey rivers extends at the surface to station 154. Arctic Bottom Water is seen as lying beneath the rising Atlantic Water in stations 61, 77, and 154. A T-S diagram (Figure 13) shows the same section as A-11; Arctic Surface Water at stations 149, 152, and 154; the sharply peaked Atlantic Water at stations 149, 152, and 154; Arctic Bottom Water at stations 61, 77, and 154; and a scattering of values for surface runoff.

Two current stations were occupied on this survey. The first was a 4 hour station taken during an extensive shoal survey in the central Kara Sea. The second was a 24 hour station located 30 miles west of the western entrance to Proliv Vilkitskogo. Table III lists the bottom current data obtained on the second current station. The bottom current at this station set slightly south of west and had a range of 0 to 0.3 knot with an average speed of 0.2 knot.

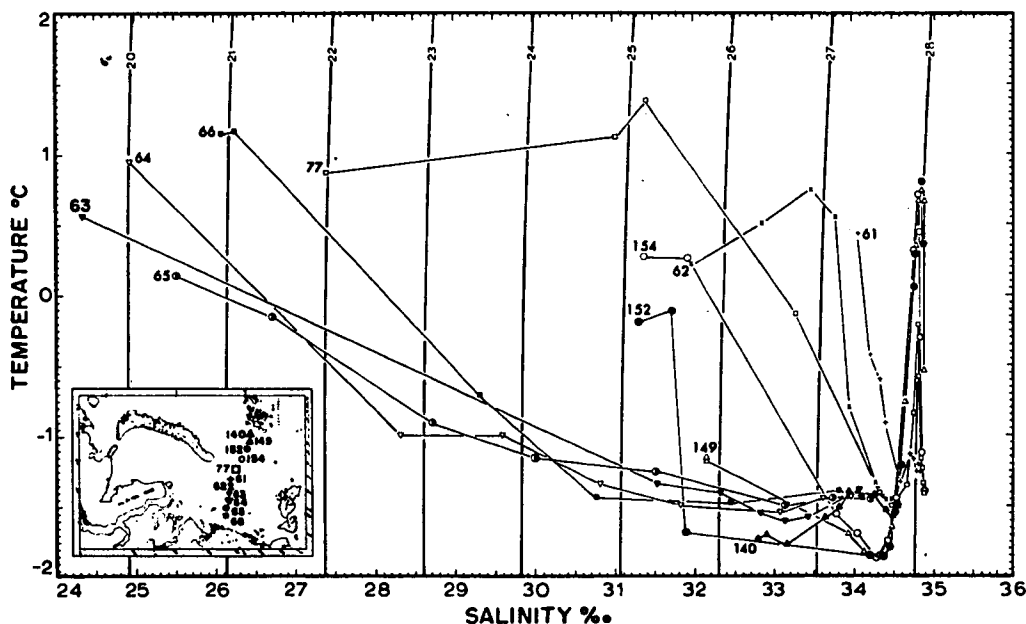


Figure 13. Temperature/Salinity Diagram for a Selected Line of Stations (Cross Section J-J', see Figure A-1)

TABLE III. Bottom Current Data at 24-Hour Station

TIME Z	CURRENT SPD. km.	CURRENT DIRECT. °T.	TIME Z	CURRENT SPD. km.	CURRENT DIRECT. °T.
17/1630	0.08	---	30	0.16	225
45	0.00	---	45	0.18	225
1700	0.06	310	0500	0.12	225
15	0.02	---	15	0.06	225
30	0.20	270	30	0.10	225
45	0.30	265	45	0.16	225
1800	0.24	245	0600	0.16	225
15	0.10	240	15	0.12	225
30	0.32	240	30	0.20	225
45	0.14	245	45	0.28	225
1900	0.12	225	0700	0.10	225
15	0.10	225	15	0.14	225
30	0.06	225	30	0.30	225
45	0.06	225	45	0.20	225
2000	0.10	225	0800	0.24	225
15	0.02	225	15	0.20	225
30	0.10	225	30	0.24	225
45	0.12	225	45	0.26	225
2100	0.10	225	0900	0.20	225
15	0.10	225	15	0.18	225
30	0.20	225	30	0.16	225
45	0.14	225	45	0.18	225
2200	0.28	225	1000	0.12	225
15	0.14	225	15	0.18	225
30	0.24	230	30	0.10	230
45	0.12	225	45	0.18	220
2300	0.14	225	1100	0.12	225
15	0.12	230	15	0.08	225
30	0.10	230	30	0.10	225
45	0.12	230	45	0.08	230
18/0000	0.10	225	1200	0.04	225
15	0.02	225	15	0.04	260
30	0.10	225	30	0.14	260
45	0.14	230	45	0.08	245
0100	0.12	230	1300	0.04	245
15	0.14	230	15	0.04	270
30	0.18	230	30	---	---
45	0.14	230	45	0.02	---
0200	0.12	225	1400	0.04	310
15	0.16	225	15	0.02	---
30	0.13	225	30	0.04	310
45	0.24	225	45	0.02	---
0300	0.20	225	1500	0.04	270
15	0.22	225	15	0.04	260
30	0.18	225	30	0.02	260
45	0.14	225	45	0.08	255
0400	0.08	225	1600	0.10	255
15	0.08	225	15	0.12	225

At the same time that subsurface currents were being measured, surface currents were estimated by plotting the tracks of icebergs. The surface current measured in this manner set slightly north of west and had an average speed of 0.5 knot. A 15-knot wind from 130° T undoubtedly was responsible for much of the surface water

movement, rather than long-term wind patterns. Local winds east of Proliv Vilkitskogo likely were responsible for the movement of water through this shallow strait.

The water movement and the resultant changes in water characteristics are shown in Figure 14. The variations in values of observed properties seem to have occurred mostly above 20 meters with salinity least affected. These observations indicate that above 20 m the surface layers east of the strait have values that correspond closely in salinity to those west of the pass. However, in the other parameters measured, e.g. reactive silicate, reactive phosphorus, and pH, the waters differ markedly.

This can be compared with changes in temperature and salinity taken at three stations repeated after a six week interval (Figure 15). As might be expected, the longer time interval resulted in larger changes in water conditions.

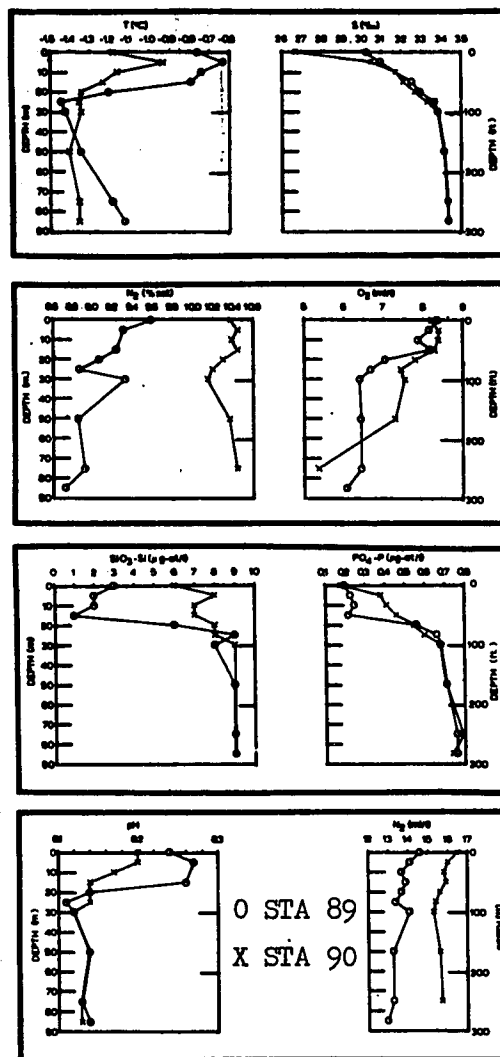


FIGURE 14.

**Changes in Various Parameters
at 24-Hour Anchor Station
Located Near the Western
entrance to Proliv Vilkitskogo**

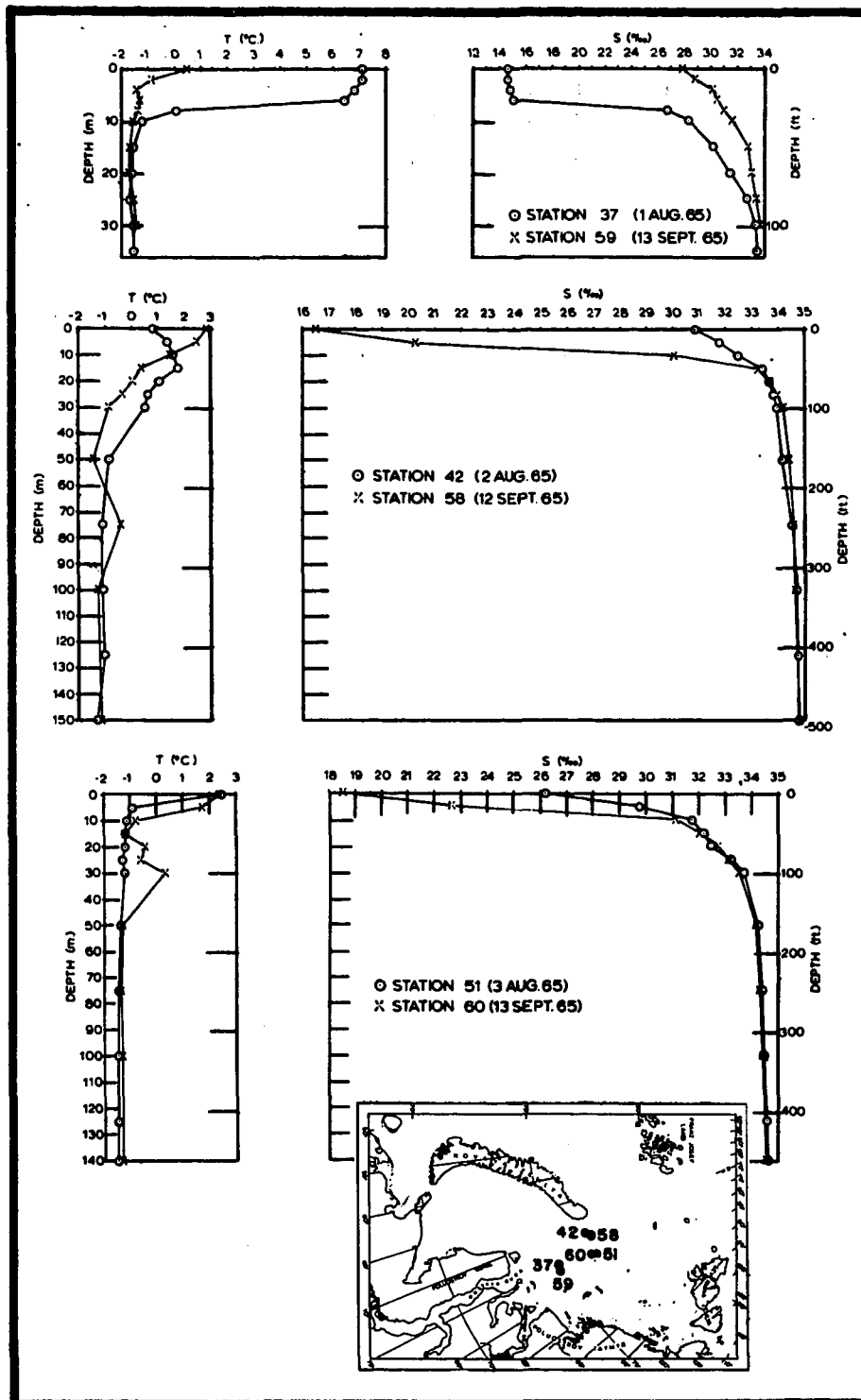


FIGURE 15. Temporal Changes in Kara Sea

The ice conditions (Figure 3) confirm the flow of water from the rivers. The Pechora River inflow had melted the ice in the lower Kara Sea at station #3 while the warm waters of the Ob River moving towards Novaya Zemlya produced ice free conditions in this area. The permanent ice pack along the northernmost line of stations was affected by the combined flow of the Ob-Yenisey towards station #114.

Appendix A depicts the water masses in cross section. The warm Pechora Current appears centered at station #3 in Figure A-2, as in Figure 3. The cold, -1.5° C, Arctic Surface Water and influx of warm, $+0.0^{\circ}$ C river runoff are clearly shown as one proceeds north along the line of sections. In Figure A-9, the first appearance of Atlantic Water occurs around the northern end of Novaya Zemlya. Figure A-11, taken along the axis of the Svyataya Anna Trough shows rising Atlantic Water roughly parallel to the bottom slope. The bathymetric chart (Figure 11) indicates three areas where the Svyataya Anna Trough is incised by deep canyons. The first is along the line depicted in Figure A-11. The second is at the north end of Novaya Zemlya (Figure A-23). This profile is very similar to A-11. The third is a small canyon incising the east wall of Svyataya Anna Trough, west of Ostrov Ushakova. This valley along the eastern margin of the Central Kara Plateau moves deep Atlantic Water directly up the slope (Figure A-18) towards station #134. Both temperature and salinity confirm this movement.

Appendix B is map views of the parameters: temperature, salinity, silicate, dissolved oxygen, reactive phosphorus, and pH. These maps were computer drawn, and show an internal consistency

that would not be achievable manually. Five levels were taken to represent water movement: surface, 5 meters, 25 meters, 50 meters, and 100 meters. As expected, temperature (Figure B-1) and salinity (Figure B-2) mark the movement of surface waters. This is most clearly seen in the surface and 5 m views. Dissolved silicate proved to be an even better tracer for river runoff, and an interesting secondary lobe of high silicate water appears (Figure B-3) corresponding to the outflow of the Pyasina River. Unexpectedly, pH values at the surface and near surface (Figure B-6) also show a close correspondence to the outflow of the rivers. Reactive phosphorus, and to a lesser extent oxygen confirm this movement. It is evident that the bulk of the river runoff moves almost directly north towards the island of Oxtrov Vize, with an offshoot, presumably from the Ob River, moving towards the north end of Novaya Zemlya. The movement of deeper waters begins with the 25 m map view. Rising Atlantic Water appears off the tip of Novaya Zemlya and along the canyon (Figure B-13). At 50 m (Figure B-19) and 100 m (Figure B-24) the temperatures continue these features, and at 100 m a third canyon is shown, near station #134 (Figure B-24). Starting with 5 m (Figure B-10) and continuing with 25 m (Figure B-16) and 50 m (Figure B-21) reactive phosphorus marking river runoff is an order of magnitude higher than values observed in the rest of the Kara Sea. In particular, the values are highest over the canyon head along the line J-J' (Figure A-11). Since this line appears to be an axis of a canyon and a pathway of Atlantic Water, profiles of dissolved oxygen, pH, silicate and reactive phosphorus were drawn (Figures 16-19). It is evident from these views that there is

FIGURE 16.
 Cross Section
 of Oxygen
 along Line J-J'

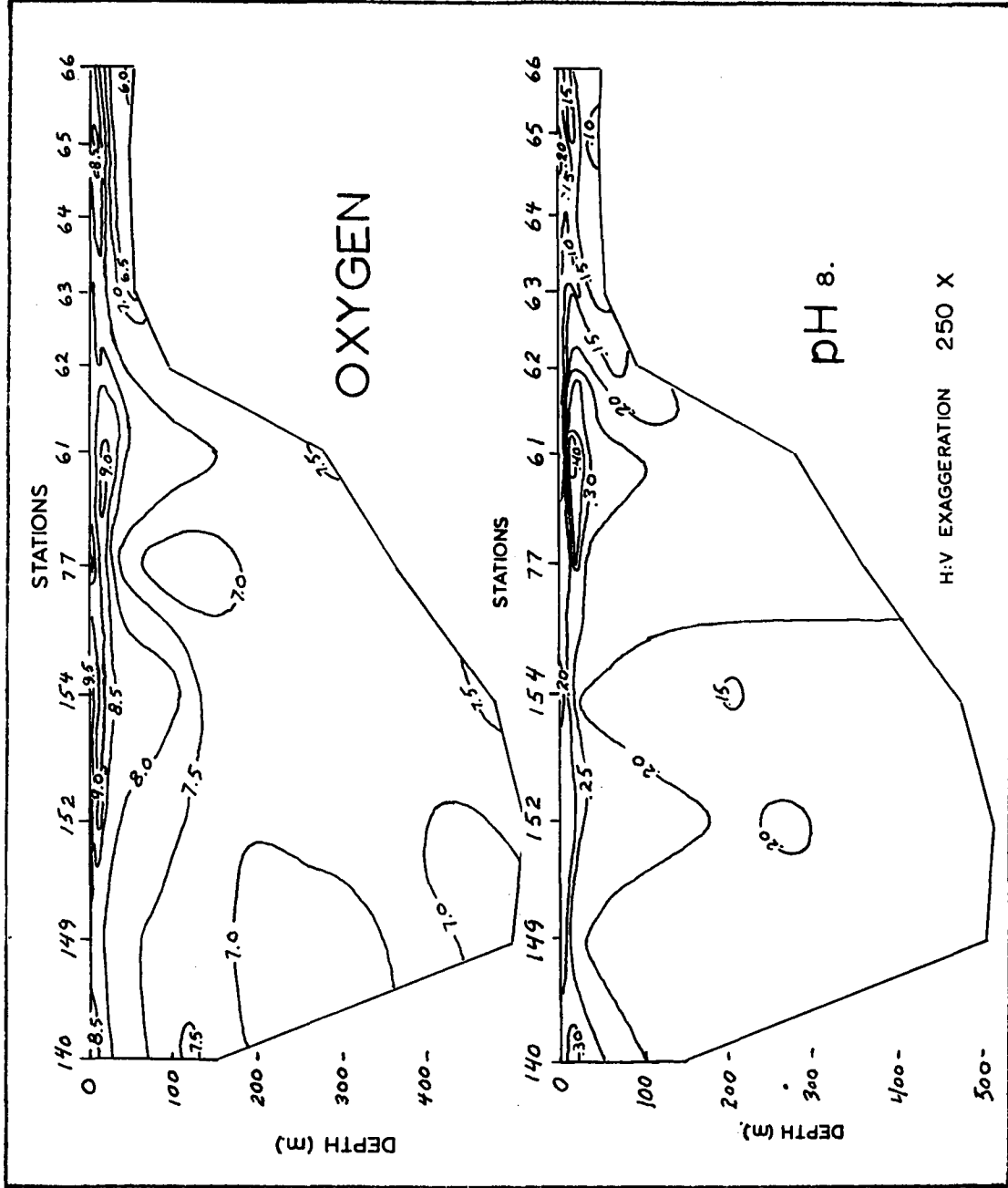


FIGURE 17.
 Cross Section
 of pH along
 Line J-J'

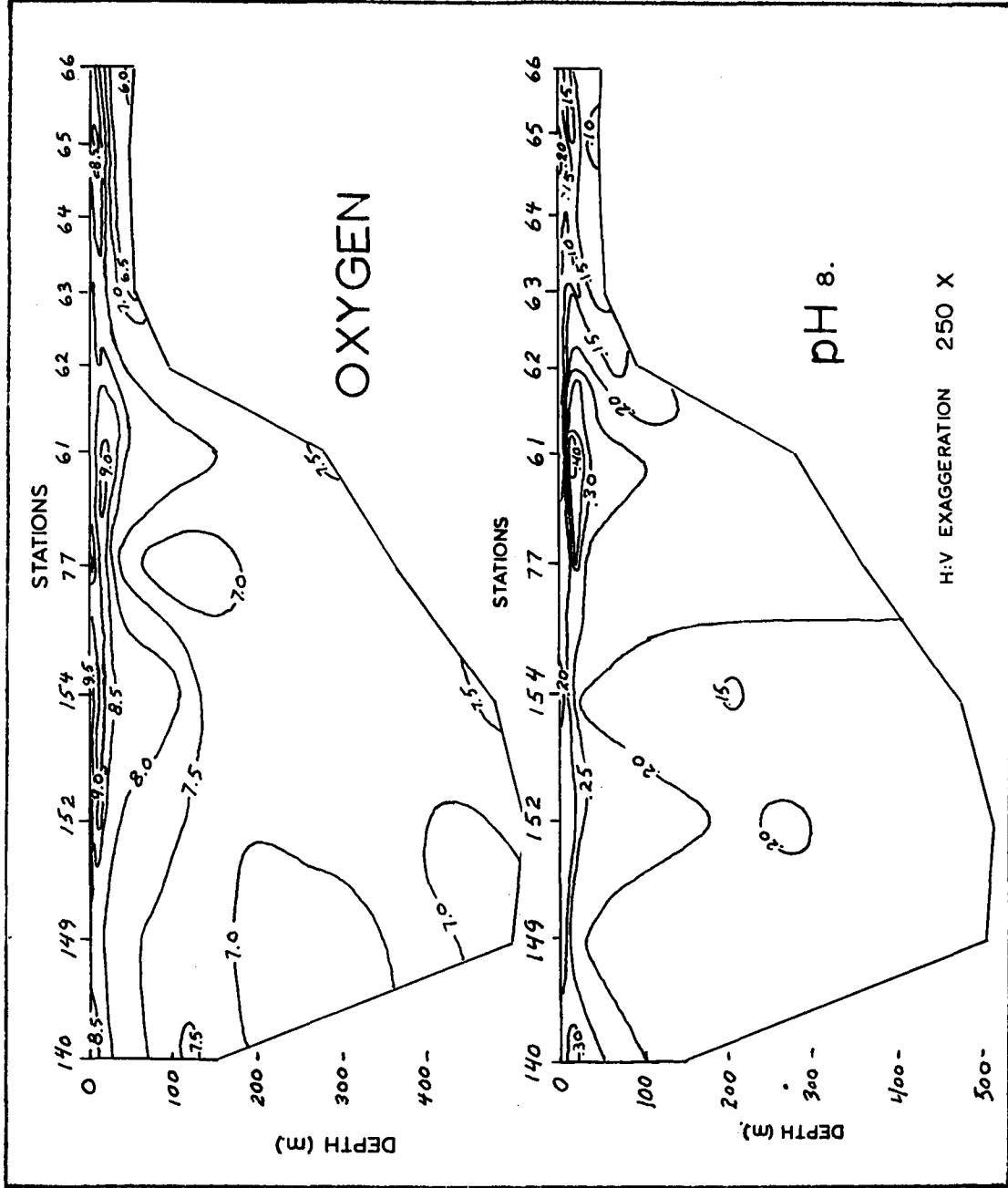


FIGURE 18.
Cross Section
of Silicate
along Line J-J'

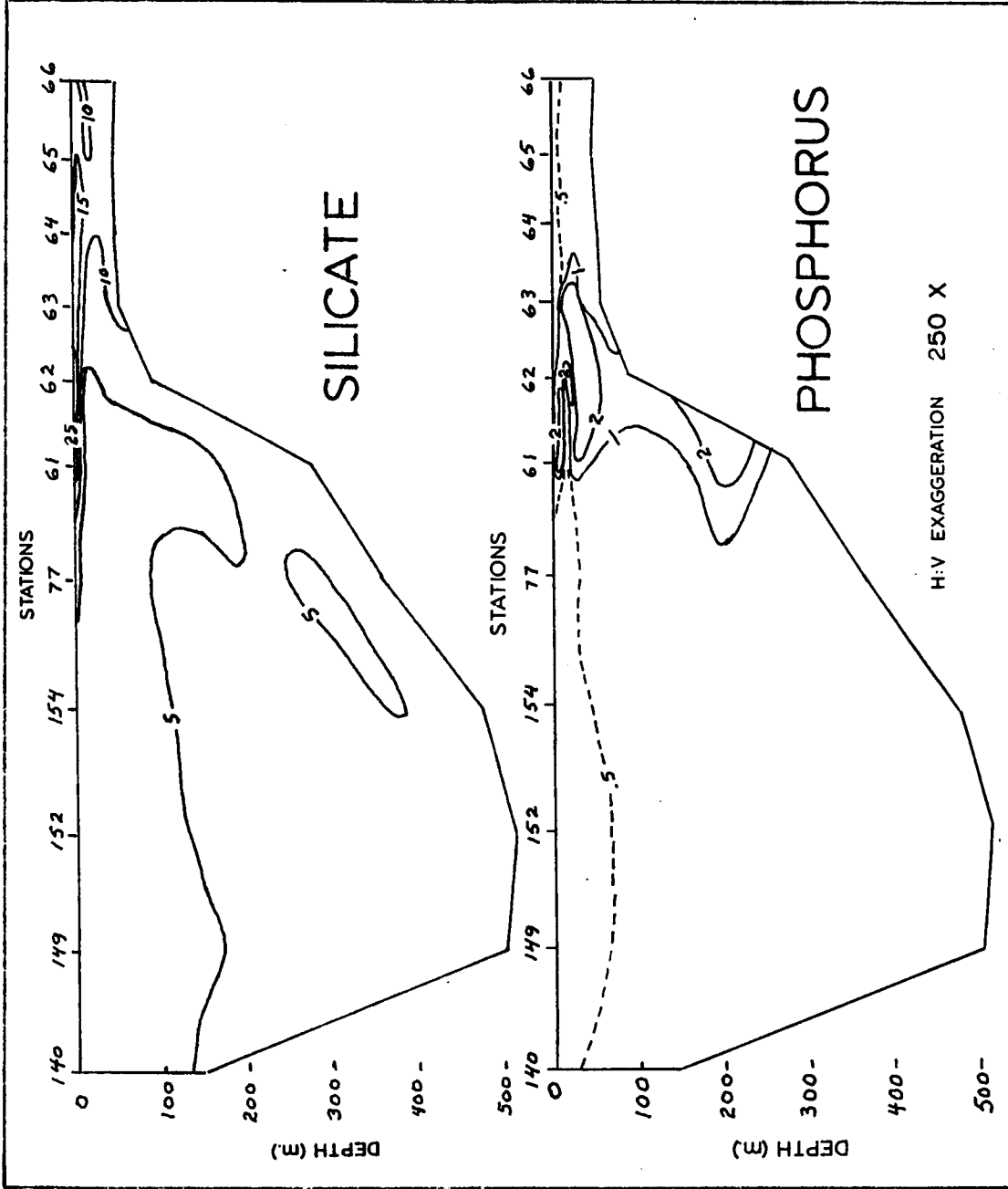


FIGURE 19.
Cross Section
of Phosphorus
along Line J-J'

a vertical sinking of nutrient rich water down the slope of the canyon to offset the upwelling of Atlantic Water. An interesting feature is how well the temperature at 100 m, silicate at 100 m, and phosphate at 100 m (Figure B-24-27) mark the inflow of Atlantic Water into the Kara Sea along the western side of the Voronin Trough.

Conclusions. Our physical and chemical data indicate that there are six water masses that either originate in or enter the Kara Sea. They are Continental Runoff, the bulk of which goes directly north along the west side of the Central Kara Plateau; an offshoot from the Ob River which moves toward the northern end of Novaya Zemlya; and the remainder along the coast of the Taymyr Peninsula. Atlantic Water which travels up the Svyataya Anna Trough and mixes with river runoff in three canyons which incise the Svyataya Anna Trough; an inflow from the Barents Sea; and a minor inflow in the southern Kara Sea from the Pechora River. Arctic Surface Water which forms in the Kara Sea and is well developed at depths of 50-75 m in a number of areas. Residual Water which is cold and highly saline and found in the East Novaya Zemlya Trough in the bottom depths. Laptev Sea Water which enters the Kara Sea through the Vilkitskogo Strait, and probably does not constitute a significant fraction of Kara Sea water. Arctic Bottom Water which was the densest of the water masses found in the Kara Sea, and lies below the North Atlantic Water moving up the Svyataya Anna and Voronin Troughs.

The Laptev Sea Water was determined (Table III) to be moving into the Kara Sea through the Vilkitskogo Strait. Prior to this survey (U.S.N. Hydrographic Office, 1958) it was believed that

the water movement was into the Laptev Sea through this passage, not the reverse.

Computer contoured maps have an advantage in that minor features, which possibly would be missed if contoured by hand, are highlighted. This is shown by repetition of features at exactly the same location. A good example is the similarity of all six parameters where the Yenisey River crosses the 25 m contour (Figures B-13-18).

The minor water constituents of dissolved oxygen, pH, silicate, and reactive phosphorus proved very useful in tracing the path of the water masses into and across the Kara Sea. Silicate (Figure B-9) and reactive phosphorus (Figure B-16) were particularly good.

Atlantic Water moving up the Svyataya Anna Trough was found to be rising and mixing in three canyons which incise the large Svyataya Anna Trough. A detailed bathymetric chart (Figure 11) was necessary to locate these canyons. Temperature at 50 m (Figure B-19) and 100 m (Figure B-24) further isolated these features. This study indicates that the primary mixing of the Atlantic Water with the overlying Arctic Surface Water and Continental Runoff occurs in these three areas. Hanzlick and Aagaard (1980) recognized one of these canyons. The exchange of heat should also occur here, and the existence of a semipermanent polynya confirms the view.

It is generally agreed that Arctic Bottom Water forms in the Greenland-Norwegian seas (Coachman and Aagaard, 1974). This water mass travels with and below Atlantic Water as it traverses the Arctic Ocean to move into and up the western side of the Svyataya Anna and Voronin Troughs. In the Kara Sea, there appears to be

some bottom water which moves down the eastern side of the Svyataya Anna Trough into the Arctic Ocean. This bottom water originates by the freezing of ice and the resulting vertical convection carrying salt to the deeper water. After an examination of sediments from the NORTHWIND survey, Andrew and Kravitz (1974) postulated this bottom current along the western edge of the Central Kara Plateau to explain distribution of sediments in the Svyataya Anna Trough. The same explanation seems to best fit the vertical movement of the nutrient rich bottom water shown in profiles of temperature, salinity, silicate, and phosphorus, along the canyon J-J' (Figure A-11 and Figures 16-19). Sections taken across the mouth of the Svyataya Anna Trough (Figures A-16-20) seem to confirm this movement, and particularly three longitudinal sections (Figures A-21-23) that show bottom water rising in an easterly direction.

Examination of the water movement in the Kara Sea particularly the Atlantic Water indicates topographic control or steering. Topographic control of the spreading of the Kara Sea waters was suggested by Hanzlick and Aagaard (1980). Certainly, deep Atlantic Water entering the Kara Sea is controlled by the Svyataya Anna Trough topography.

Hanzlick and Aagaard (1980), using data from the NORTHWIND cruise, proposed that a portion of Atlantic Water entering the Kara Sea turns along the 600 m contour and exits the area almost immediately. An alternate explanation is that rather than a loss from the core depth (300 m) as suggested by Hanzlick and Aagaard, the top layer of Atlantic Water exits up the canyon as observed at station #134 (Figure A-18). It should be noted that the core of Atlantic

Water (Figure A-18) is deeper, i.e., the 0° contour is at 112 m at station #117 (Figure A-17), 145 m at station #136, and 200 m at station #135 (Figure A-18).

Arctic Surface Water with a salinity of 33.5-34.5 ‰ and a temperature of less than -1.5° C is found at depths of 50 to 70 meters in all the deeper parts of the Kara Sea. Yet, nowhere in the Kara Sea is Arctic Surface Water found at the surface. At the surface in the northern areas of the Kara Sea, the temperatures are low enough, but the salinity is too low. Examination of a T-S diagram (Figure 20) of the northernmost line of stations (Figure A-16) shows that surface waters are at the maximum temperature for the given salt content. Profiles taken down the axis of the Svyataya Anna Trough (Figures A-21-23) indicate that warmer river runoff overrides the more dense Arctic Surface Water and causes a mixing with the more saline Atlantic Water below. This process was taking place during the time of the NORTHWIND survey. However, it is believed that the winter ice production with concentration and convection of salt due to freezing would cause greatly increased formation of this water.

River runoff produces an annual layer of freshwater about 1.3 m thick if spread uniformly over the entire Kara Sea. Estimates of average thickness of ice formed annually are similar, about 1.5 m. The export of this ice would match the river input. Examination of ice conditions at the time of this survey (Figure 3) when ice was at a minimum in the Kara Sea, raises the question as to where the ice would be exported. The entrance in the lower Kara, Proliv Karskiye Vorota, is the site of an inflow from the Pechora River. Proliv Borisa Vilkitskogo, the entrance to the Laptev Sea, recorded a current

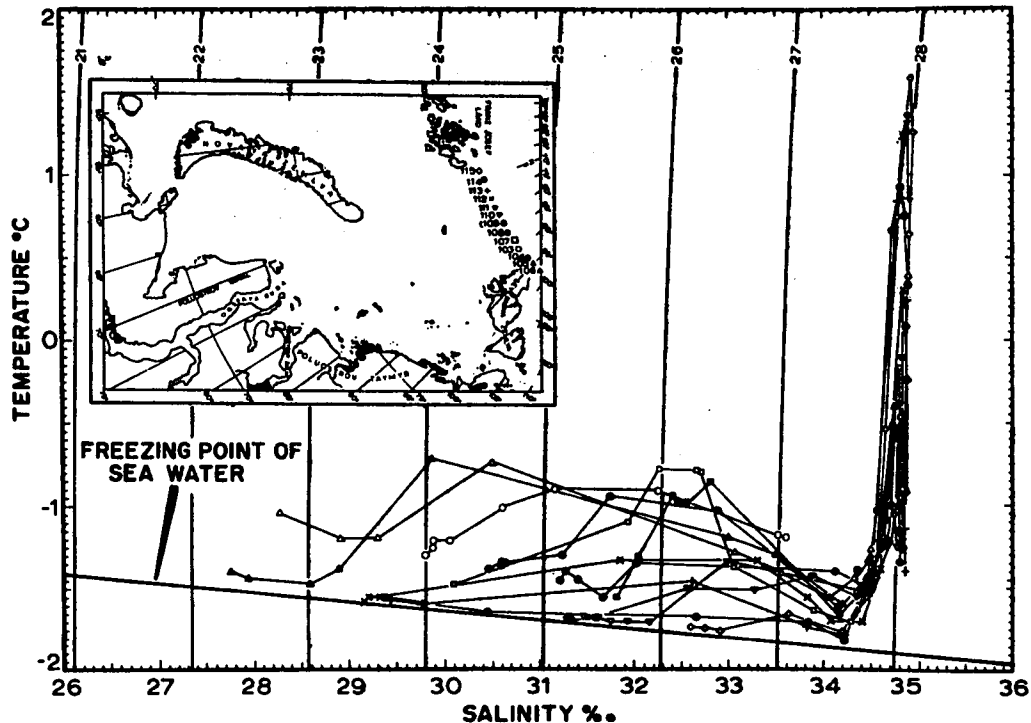


Figure 20. Temperature/Salinity Diagram for a Selected Line of Stations (Cross Section O-O', see Figure A-1)

from the Laptev to the Kara Sea. The northern most line of stations were taken in the polar ice pack, a permanent barricade to any appreciable flow of ice to the north. The only exit is to the Barents Sea, and this study along with others [Micklin (1981) estimates $22,082 \text{ km}^3/\text{yr}$ inflow from the Barents Sea] did not find evidence of appreciable flow from the Kara into the Barents Sea. Coachman and Aagaard (1974) conclude that although transport through the Zemlya Frantsa Iosifa - Novaya Zemlya passage remains essentially unknown, there is in all probability only a small annual net flow from the Barents to the Kara Sea. Therefore, this study concludes that the ice formed in the Kara Sea essentially melts in the Kara Sea under the influence of the rising warm Atlantic Water.

SUMMARY

The Kara Sea is an area of intense mixing of Atlantic Water and Continental Runoff, the movement of both controlled in large part by the physiography of the area. There are three canyons which incise the Svyataya Anna Trough and these are where the mixing takes place.

Some Arctic Bottom Water forms in the Kara Sea and sinks under incoming Atlantic Water at the heads of the canyons along the eastern margin of the Svyataya Anna Trough. This bottom current moves into the Arctic as a countercurrent to the incoming Atlantic Water.

Arctic Surface Water is produced in the northern Kara Sea in summer by the mixing of river water and Atlantic Water. This effect takes place along the margin of the ice and probably is greatly enhanced when the ice begins to form in fall and winter. This water exits the Kara Sea northward as a surface and near surface current.

A portion of the incoming Atlantic Water rises and exits the Kara Sea almost immediately up a canyon along the northwestern edge of the Central Kara Plateau.

Ice is a significant feature of the Kara Sea. It causes convection currents which carry salt to deeper depths. It deposits ice rafted material when it melts under the influence of incoming Atlantic Water. It scores the shallow bottom as it moves along

in the form of icebergs.

REFERENCES CITED

- Aagaard, K. and L.K. Coachman. 1975. Toward an ice-free Arctic Ocean. EOS, 56(7). p. 484-486.
- Andrew, J.A. and J. Kravitz. 1974. Sediment distribution in deep areas of the Northern Kara Sea, in Marine Geology and Oceanography of the Arctic Seas, Yvonne Herman (ed). New York: Springer-Verlag. p. 231-256.
- Antonov, V.S. 1958. The role of Continental Runoff in the current regime of the Arctic Ocean. Probl. Severya. 1: 52-64. Translation.
- Bondarev, V.I., S.V. Cherkesova, V.S. Enokyan, and B.S. Romanovich. 1973. Geologic structure on Novaya Zemlya, Vaygach, Pay-Khoy, Polar Urals, and Northern Pechora, in Pitcher, M.G. (ed). Arctic Geology: Am. Assoc. Petr. Geol. Mem. 19 p. 301-308.
- Churkin, M. Jr. 1973. Geologic concepts of Arctic Ocean Basin, in Pitcher, M.G. (ed). Arctic Geology: Am. Assoc. Petr. Geol. Mem. 19. p. 485-499.
- Coachman, L.K. and C.A. Barnes. 1961. The movement of Atlantic Water in the Arctic Ocean. Arctic. 16:1:8-16.
- _____. 1962. Surface water in the Eurasian Basin of the Arctic Ocean. Arctic. 15(4):251-277.
- Coachman, L.K. and K. Aagaard. 1974. Physical oceanography of Arctic and Subarctic seas, in Marine Geology and Oceanography of the Arctic Seas, Yvonne Herman (ed). New York: Springer-Verlag. p. 1-72.
- Eskin, F.I. 1960. On the question of the influence of Atlantic Water on the upper horizons of the Arctic sea (translated). Vestnik Leningrad University No. 6, Ser. Geol. Geog. 1:153-158.
- Gakkel, Y.Y. and V.D. Dibner. 1967. Bottom of the Arctic Ocean, in Runcorn, S.K., International Dictionary of Geophysics. Elmsford, NY. Pergamon Press. 1:152-165.
- Garcia, A.W. 1973. Oceanographic observations in the Kara Sea and eastern Barents Sea. U.S. Coast Guard Oceanographic Report, CG 373-25, 99 p.

- Gordienko, P.A. 1961. The Arctic Ocean. *Scientific American*. 204(5):88-102.
- Hamilton, W. 1970. The Uralides and the motions of the Russian and Siberian platforms. *Geol. Soc. Amer. Bull.* 81:2553-2576.
- Hanzlick, D. and K. Aagaard. 1980. Freshwater and Atlantic Water in the Kara Sea. *Journal of Geophysical Research*. 85(C9): 4937-4942.
- Harland, W.B. 1973. Tectonic evolution of the Barents Shelf and related plates, in Pitcher, M.G. (ed). *Arctic Geology: Am. Assoc. Petr. Geol. Mem.* 19. p. 599-608.
- Heezen, B.C., M. Tharp, and M. Ewing. 1959. The floor of the oceans. 1: The North Atlantic: *Geol. Soc. Am. Spec. Paper* 65. 122 p.
- Johnson, G.L. and D.B. Milligan. 1967. Some geomorphological observations in the Kara Sea. *Deep Sea Research*. 14:19-28.
- Klenova, M.V. 1936. Sediments of the Kara Sea. *DAN SSSR*, 4(13):4.
- Kulikov, N.N. 1961. Sedimentation in the Kara Sea. *Sovremennyye Osadki Morey I Okeanov: 437-447*, in J.H. Kravitz (ed). 1967. U.S.N. Oceanographic Office Translations, 317 p.
- Lazukov, G.I. 1964. Variations in the level of the Polar Basin in the Quaternary Period. *Okeanologiya*. V.4. p. 174-181.
- L'vovich, M.I. 1953. Outline of hydrography of rivers of the USSR. Moscow Press of the Academy of Sciences, USSR, 323 p.
- MacInnis, J.B. 1970. MacInnis shifts from 80° F to 29° F Water. *SEAS*. 2:33.
- Meyerhoff, Howard A. and A.A. Meyerhoff. 1973. Arctic geopolitics, in Pitcher, M.G. (ed). *Arctic Geology: Am. Assoc. Petr. Geol. Mem.* 19. p. 646-670.
- Meyerhoff, A.A. 1973. Origin of Arctic and North Atlantic Oceans, in Pitcher, M.G. (ed). *Arctic Geology: Am. Assoc. Petr. Geol. Mem.* 19. p. 562-582.
- Micklin, Philip P. 1981. A preliminary systems analysis of impacts of proposed Soviet river diversions on arctic sea ice. *EOS*, 62(19). p. 489-493.
- Milligan, D.B. 1969. Oceanographic survey results of the Kara Sea - Summer and Fall 1965. U.S.N. Oceanographic Office Technical Report. TR217, p. 64.
- Murphy, J. and J.P. Riley. 1962. Determination of phosphate in

- natural waters. *Anal. Chim. Acta.* 27:31.
- Nansen, Fridtjof. 1902. *Oceanography of the North Polar Basin. The Norwegian North Polar Expedition 1893-1896, Scientific Results.* 3(9):427 p.
- Novitskiy, V.P. 1961. Permanent currents of the northern Barents Sea. *Trudy Gosudo. Okeano. Inst.* 64:1-32. Leningrad Translation No. 349. U.S.N. Oceanographic Office.
- Ostenso, N. 1974. Arctic Ocean margins, *in* *The Geology of Continental Margins*, (eds) Burk, C.A. and C.L. Drake. New York: Springer-Verlag. p. 753-763.
- Ostenso, N.A. and R.J. Wold. 1973. Aeromagnetic evidence for origin of Arctic Ocean Basin, *in* Pitcher, M.G. (ed). *Arctic Geology*: Am. Assoc. Petr. Geol. Mem. 19. p. 506-516.
- Petrow, R. 1967. *Across the top of Russia.* New York, New York: David McKay Co., Inc. 373 p.
- Saks, V.N. 1948. Quaternary period in the Soviet Arctic. *Trudy Arkicheskogo Nauchno-Issled Instituta*, 201:12-17 and 62-74, *in* J.H. Kravitz (ed). 1967. U.S.N. Oceanographic Office Translations, 338. 25 p.
- Saks, V.N. and S.A. Strelkov, 1961. Mesozoic and Cenozoic of the Soviet Arctic, *in* G.O. Raasch, (ed) *Geology of the Arctic.* Toronto: University of Toronto Press, 1. p. 48-67.
- Shpaikher, A.O. and V.P. Rusanov. 1962. Silicon distribution as a water mass indicator in Siberian shelf seas. *Problems of the Arctic and Antarctic.* 40:60-66.
- Stoll, S.J. 1967. A foraminiferal study of the Kara Sea north of 76° north latitude. Masters Thesis, Madison, Wisconsin, University of Wisconsin. 86 p.
- Strickland, J.D.H. and T.R. Parsons. 1965. *A manual of seawater analysis.* Fisheries Research Board of Canada. Bull. 125.
- Sullivan, J.P. 1963. Determination of dissolved oxygen and nitrogen in seawater by gas chromatography. U.S.N. Oceanographic Office, IMR No. 0-17-63, 40 p.
- Todd, Ruth and Doris Low. 1980. Foraminifera from the Kara and Greenland Seas, and review of Arctic studies. *Geological Survey Professional Paper* 1070:1-36.
- Turner, R.R. 1973. The significance of color banding in the upper layers of Kara Sea sediments. U.S. Coast Guard Oceanographic Report, CG 373-36, 36 p.
- United States Navy Hydrographic Office. 1958. *Oceanographic*

atlas of the Polar Seas. Part II: Arctic. Hydrographic Office Publication 705. 149 p.

- Vogt, P.R. 1968. A reconnaissance geophysical survey of the North, Norwegian, Greenland, Kara and Barents Seas and the Arctic Ocean. Doctoral Thesis, Madison, Wisconsin: University of Wisconsin. 133 p.
- Vogt, P.R. and N.A. Ostenso. 1973. Reconnaissance geophysical studies in Barents and Kara Sea - Summary, in Pitcher, M.G. (ed). Arctic Geology: Am. Assoc. Petr. Geol. Mem. 19. p. 588-598.
- Vogt, P.R. and Otis E. Avary. 1974. Tectonic history of the Arctic Basins: partial solutions and unsolved mysteries, in Marine Geology and Oceanography of the Arctic Seas. Yvonne Herman (ed). New York: Springer-Verlag, p. 83-117.
- Yermolayev, M.M. 1948. The problem of historical hydrology of seas and oceans. Geogr. Klimatol. Gidrol. p. 27-36. Translation U.S.N. Oceanographic Office No. 346.
- Zenkevitch, L.A. 1963. Biology of the seas of the USSR. Interscience Publishers. 955 p. (Translation).
- Zenkovitch, V.P., O.K. Leontiev and E.N. Nevevsky. 1960. Influence of the eustatic post-glacial transgression upon the development of the coastal zone of the USSR seas: 21st Int. Geol. Congr. Proc. pt. 10, p. 65-72.
- Zubov, N.N. 1945. Arctic Ice. Translation, U.S.N. Oceanographic Office.

APPENDIX A

DETAILED CROSS SECTIONS OF THE
WATER MASSES IN THE KARA SEA

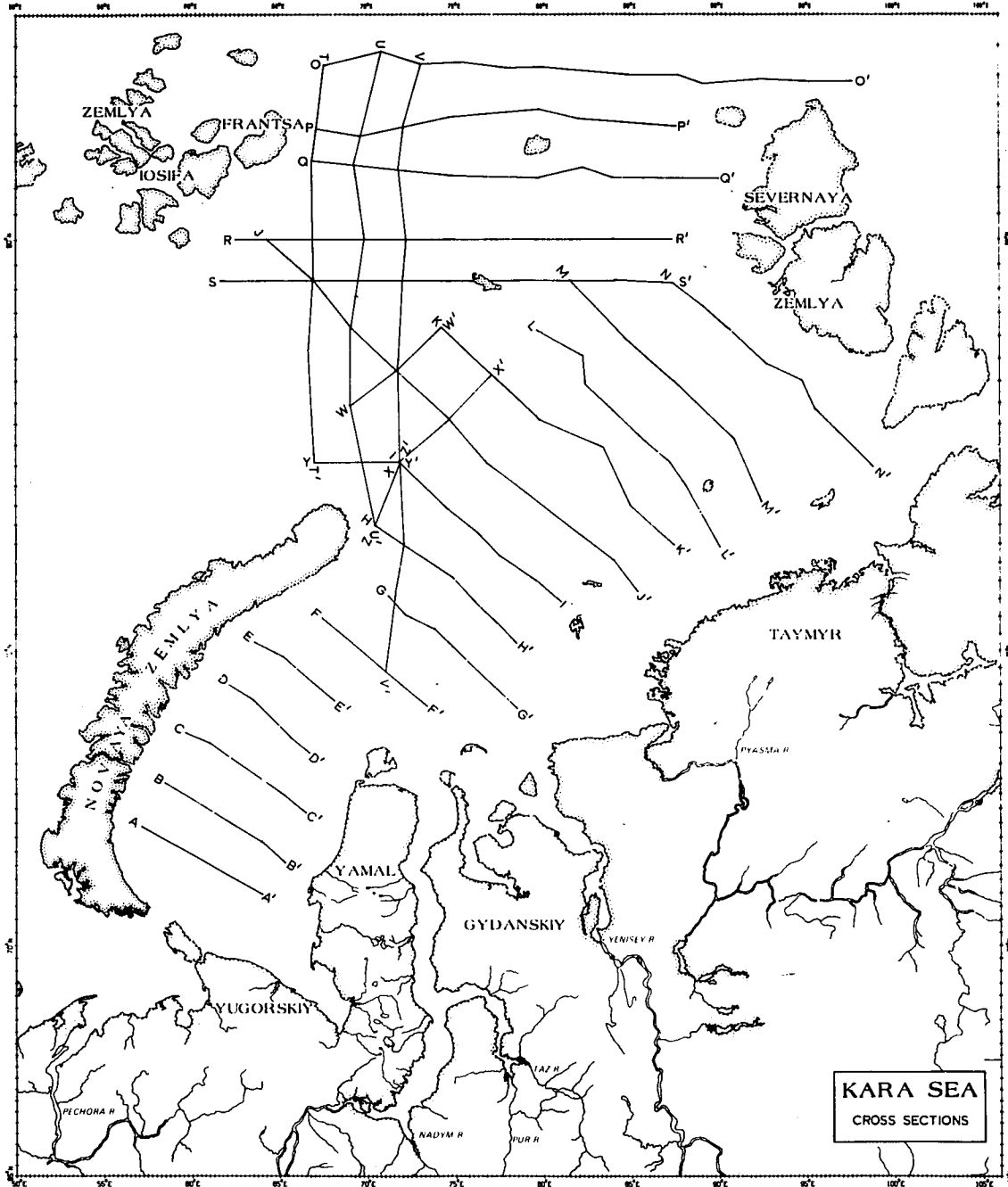


Figure A-1. Locations of Cross Sections.

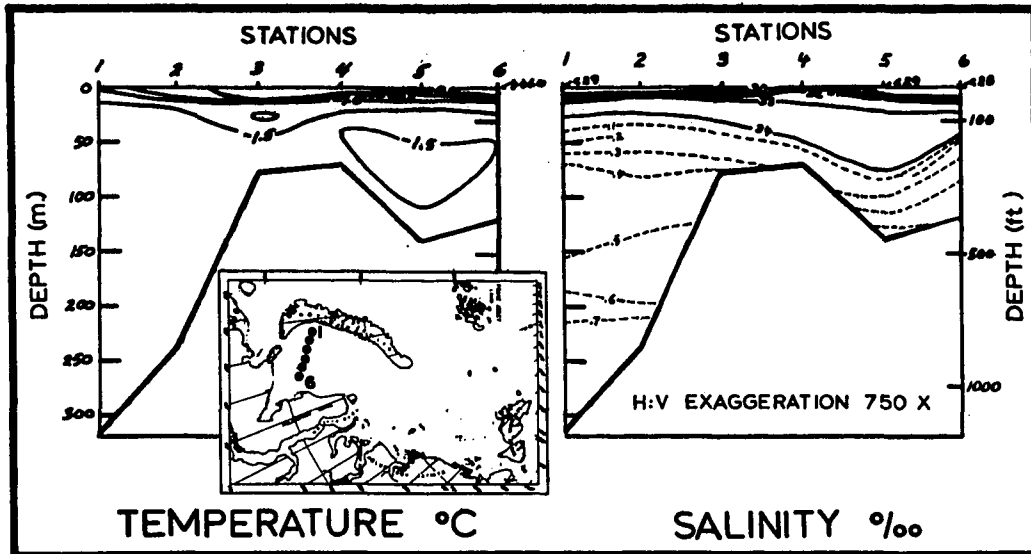


FIGURE A-2. Cross Sections of Temperature and Salinity Along Line A-A'

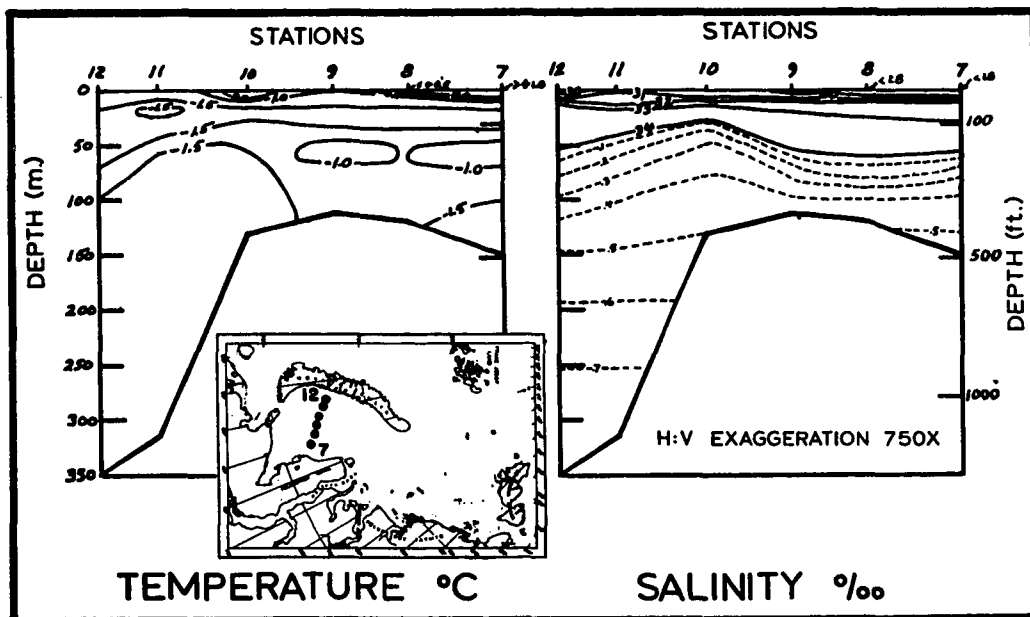


FIGURE A-3. Cross Sections of Temperature and Salinity Along Line B-B'

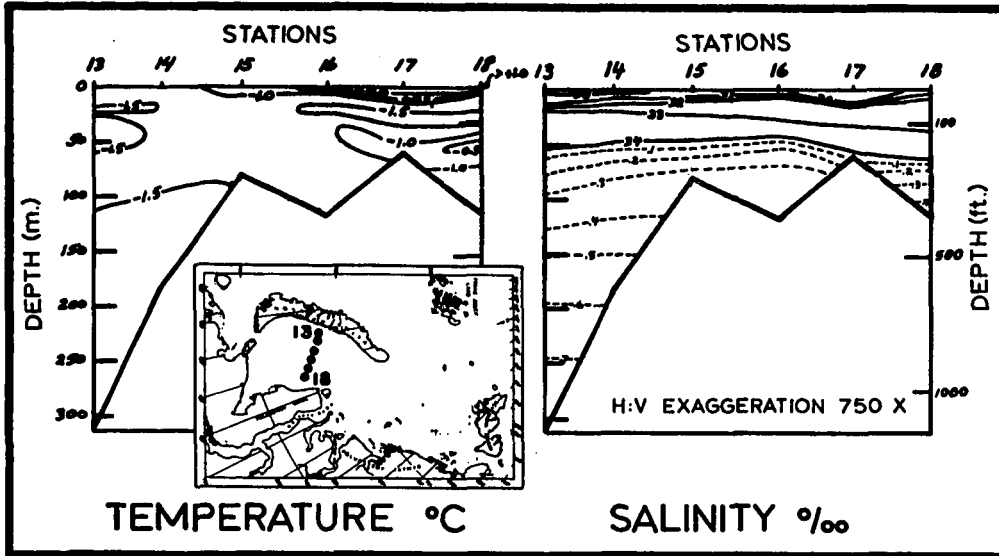


FIGURE A-4. Cross Sections of Temperature and Salinity Along Line C-C'

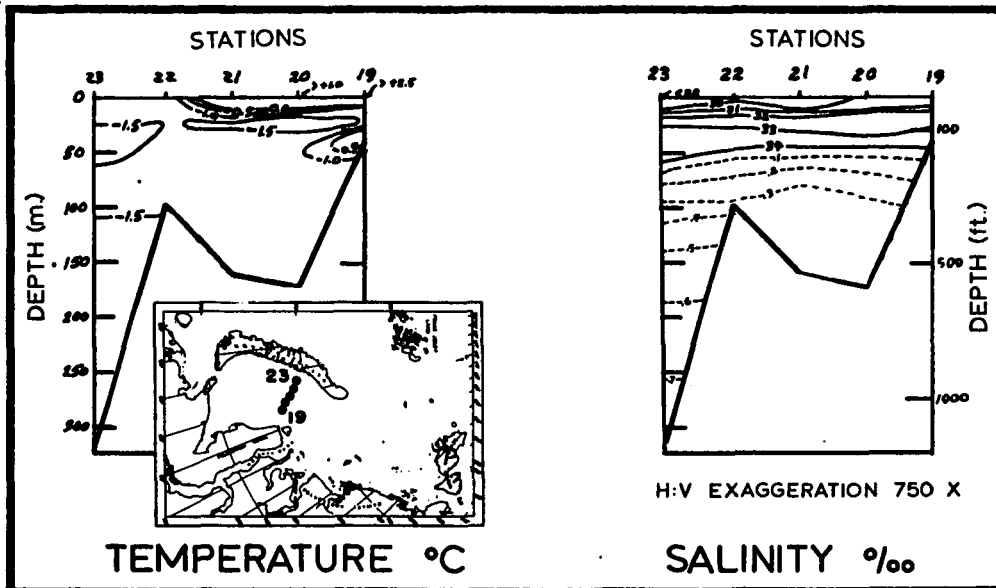


FIGURE A-5. Cross Sections of Temperature and Salinity Along Line D-D'

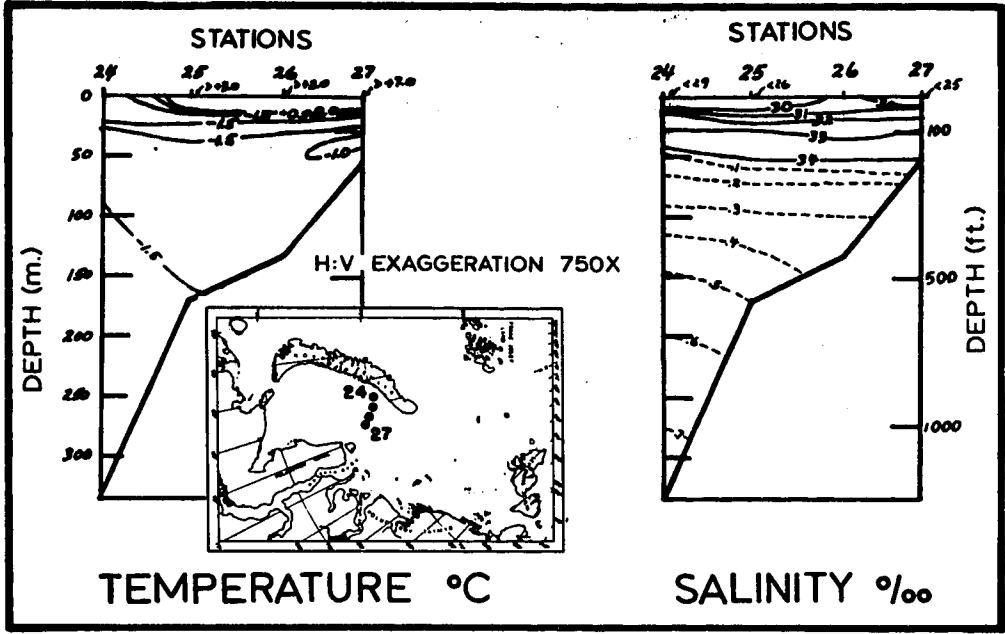


FIGURE A-6. Cross Sections of Temperature and Salinity Along Line E-E'

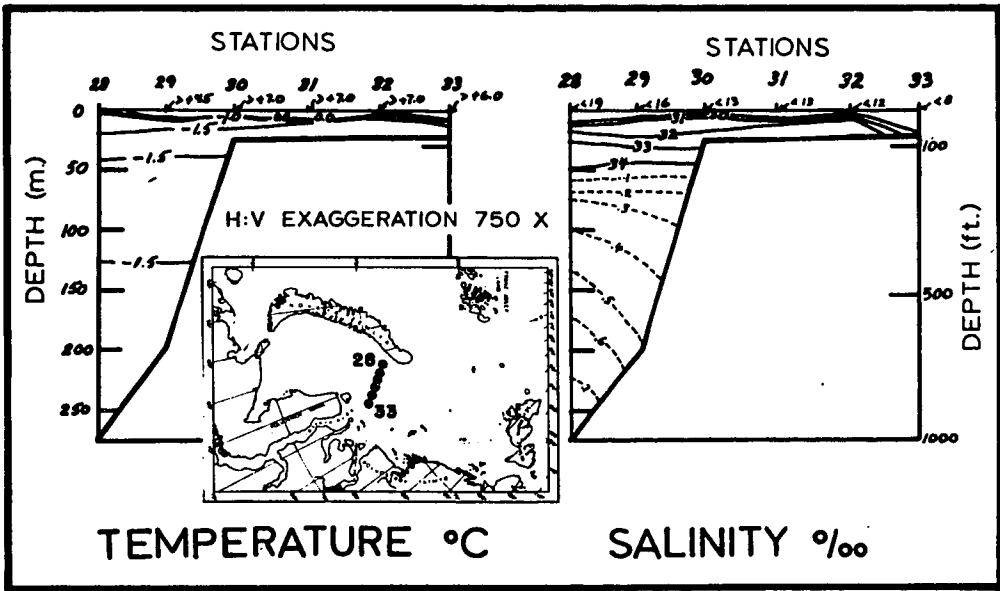


FIGURE A-7. Cross Sections of Temperature and Salinity Along Line F-F'

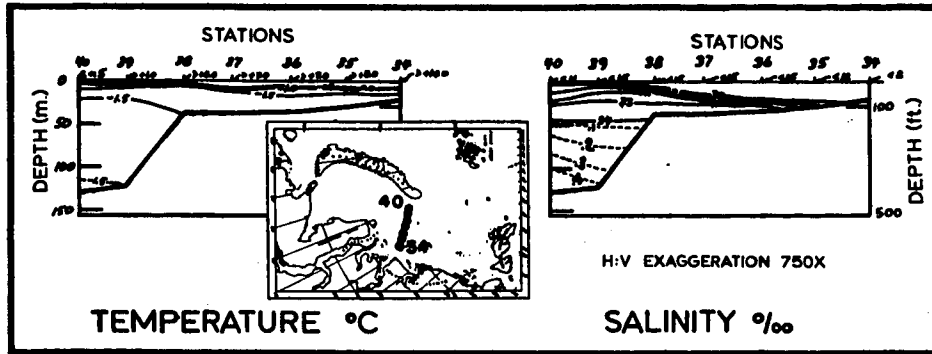


FIGURE A-8. Cross Sections of Temperature and Salinity Along Line G-G'

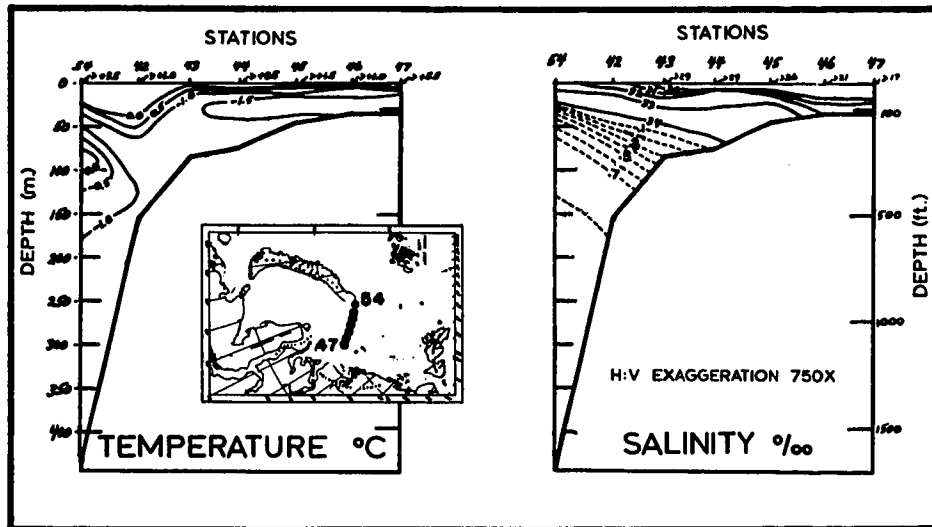


FIGURE A-9. Cross Sections of Temperature and Salinity Along Line H-H'

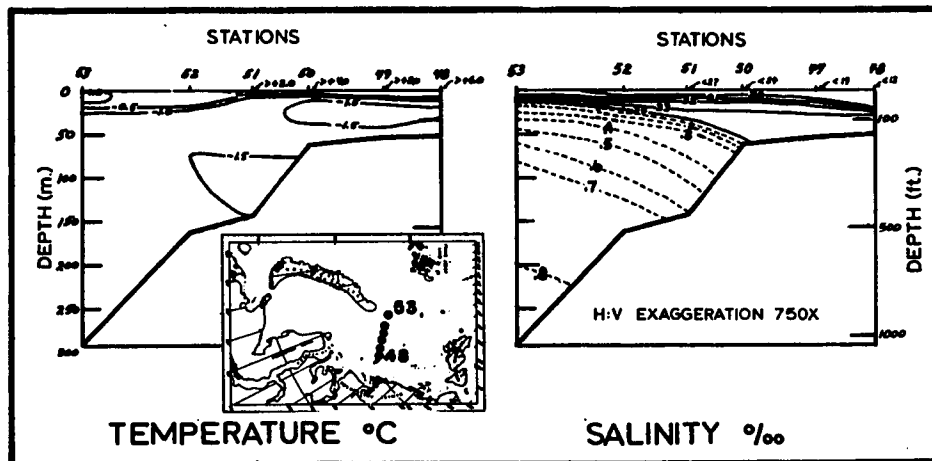


FIGURE A-10. Cross Sections of Temperature and Salinity Along Line I-I'

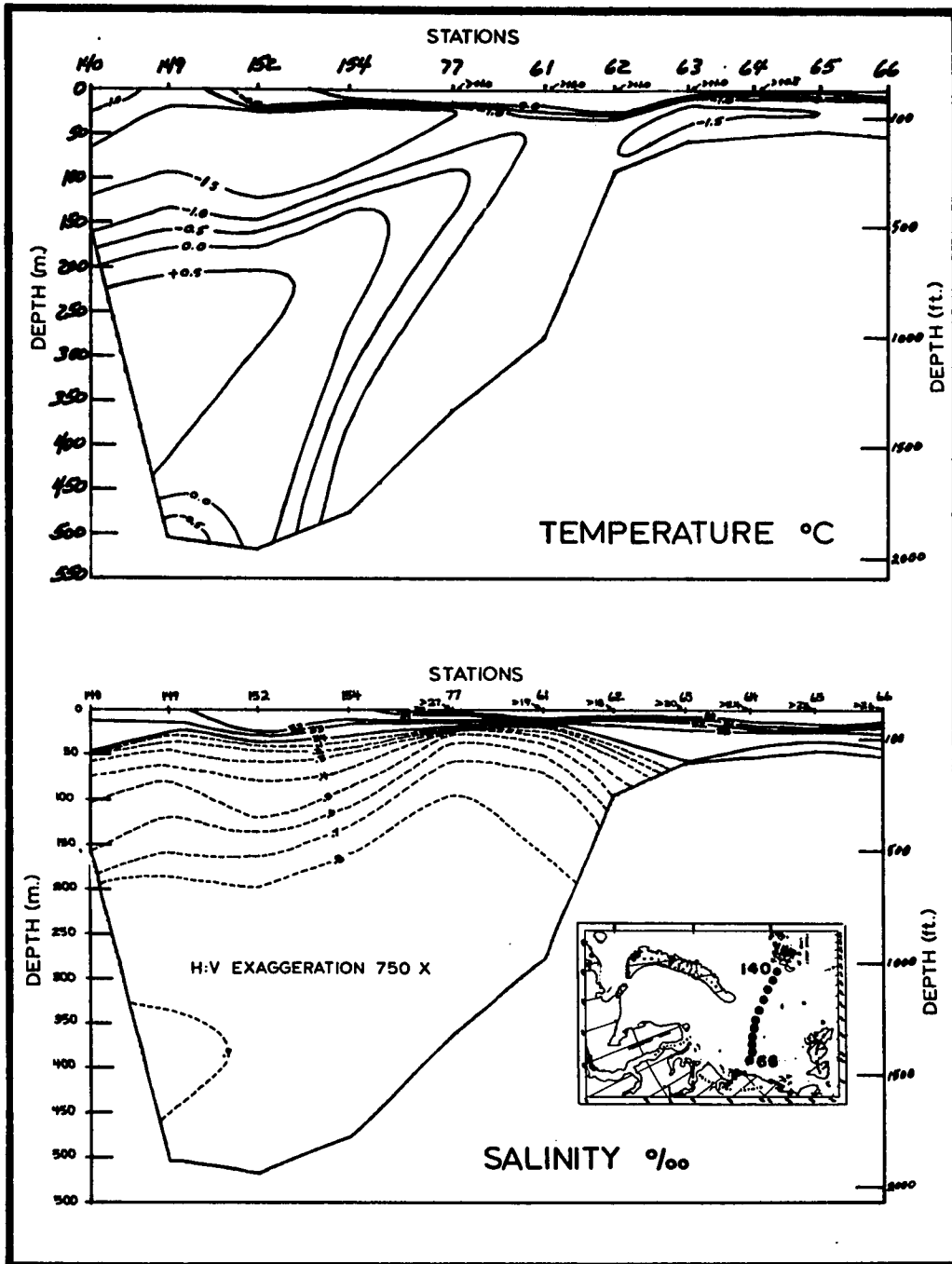


FIGURE A-11. Cross Sections of Temperature and Salinity Along Line J-J'

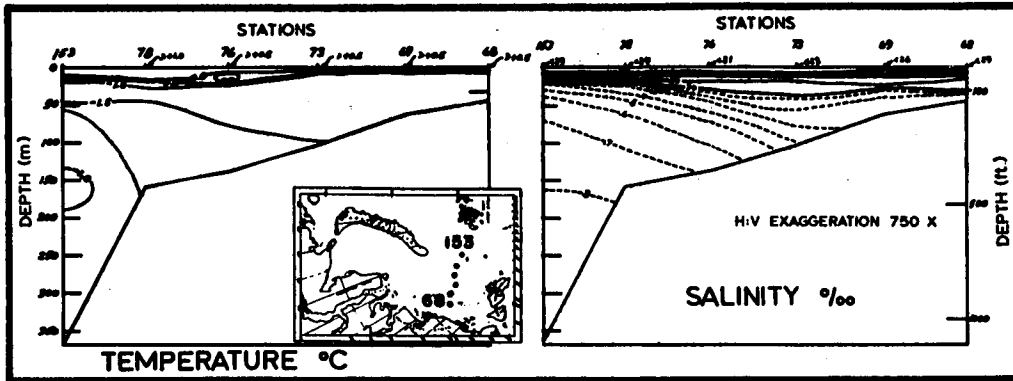


FIGURE A-12. Cross Sections of Temperature and Salinity Along Line K-K'

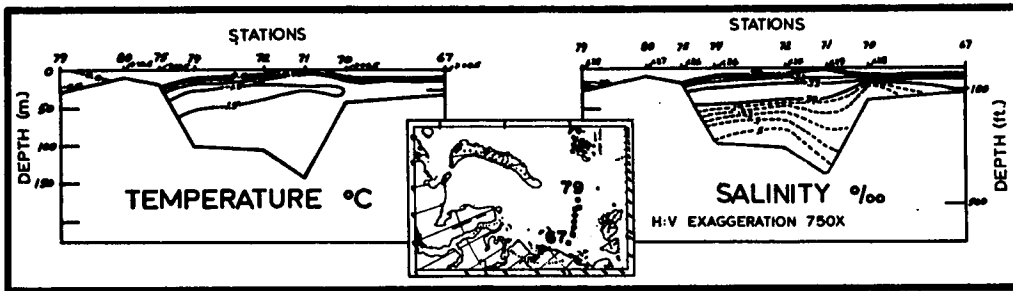


FIGURE A-13. Cross Sections of Temperature and Salinity Along Line L-L'

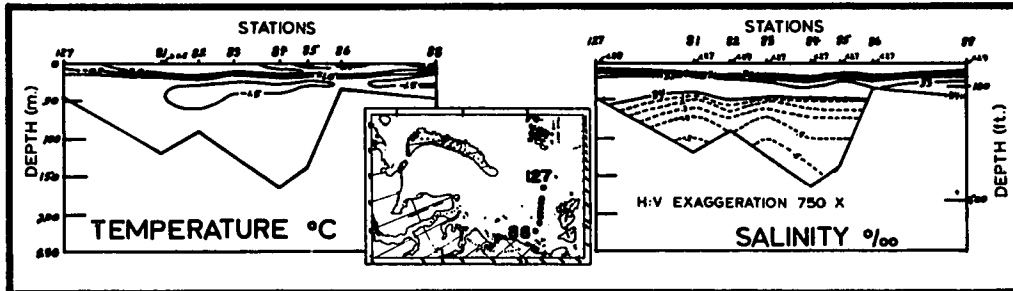


FIGURE A-14. Cross Sections of Temperature and Salinity Along Line M-M'

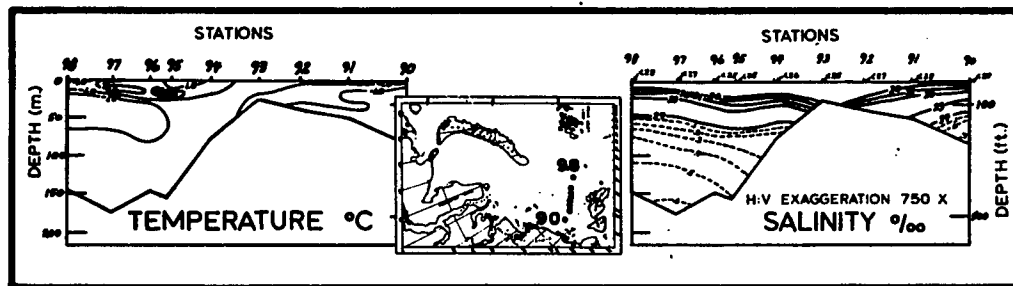


FIGURE A-15. Cross Sections of Temperature and Salinity Along Line N-N'

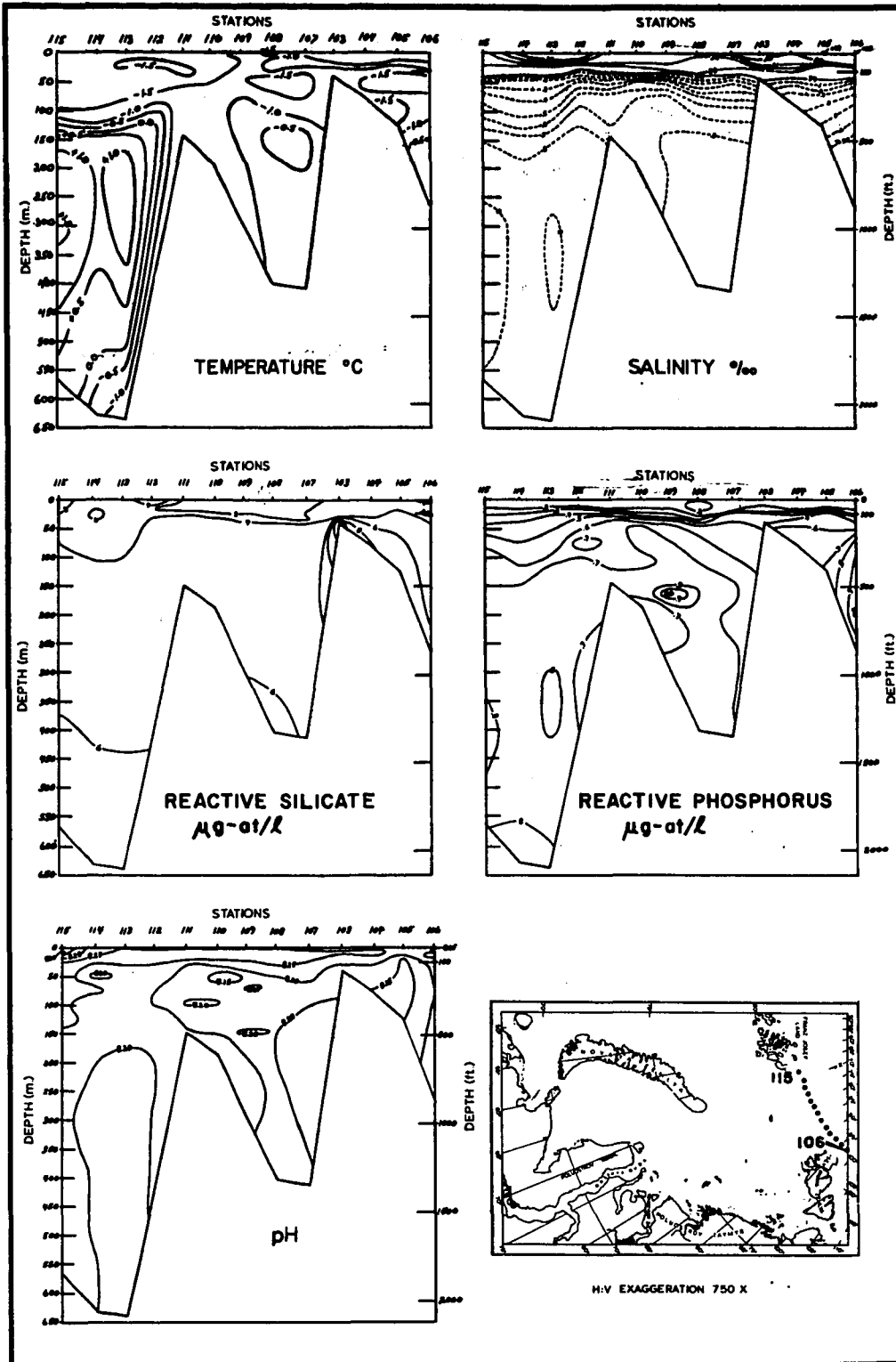


FIGURE A-16. Cross Sections of Temperature, Salinity, Reactive Silicate, Reactive Phosphorus, and pH Along Line O-O'

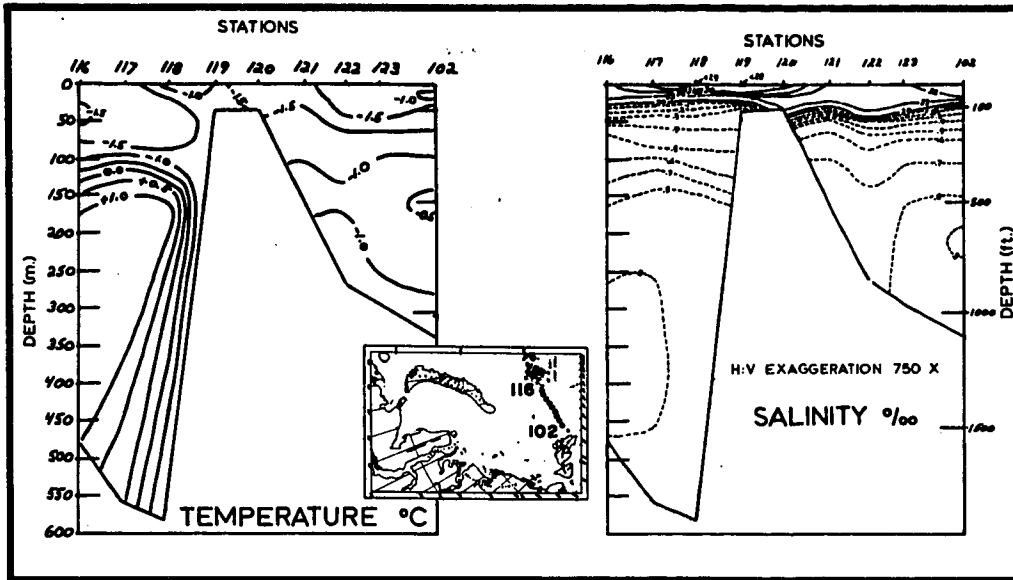


FIGURE A-17. Cross Sections of Temperature and Salinity Along Line P-P'

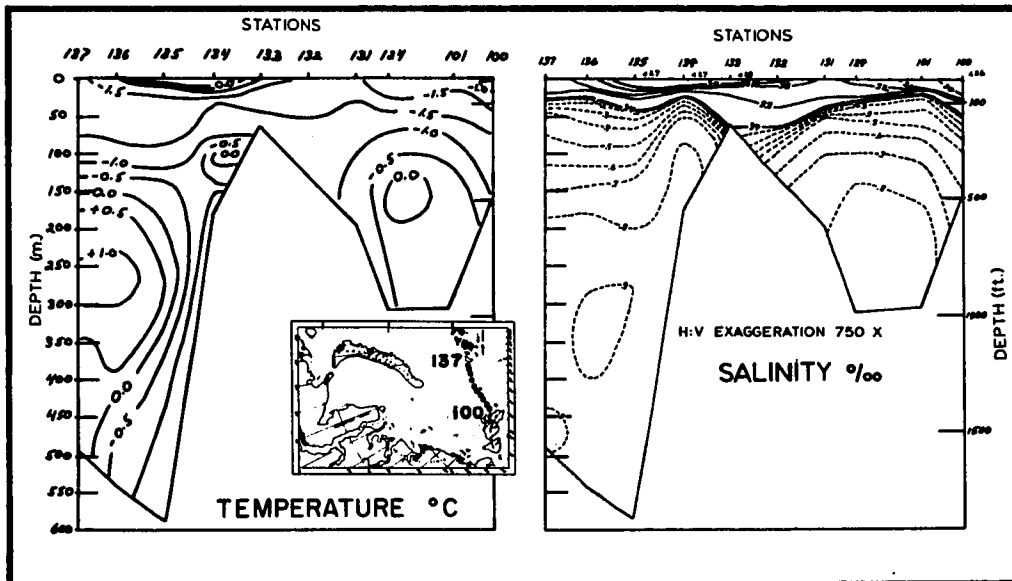


FIGURE A-18. Cross Sections of Temperature and Salinity Along Line Q-Q'

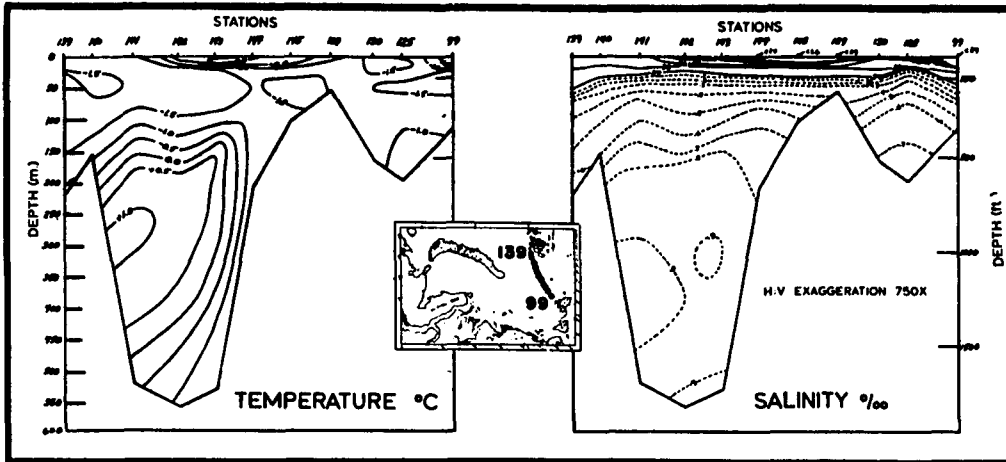


FIGURE A-19. Cross Sections of Temperature and Salinity Along Line R-R'

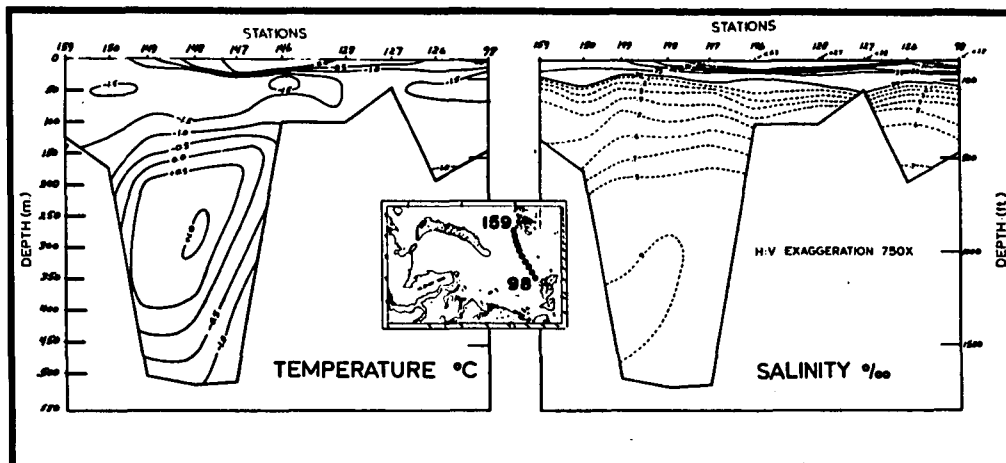


FIGURE A-20. Cross Sections of Temperature and Salinity Along Line S-S'

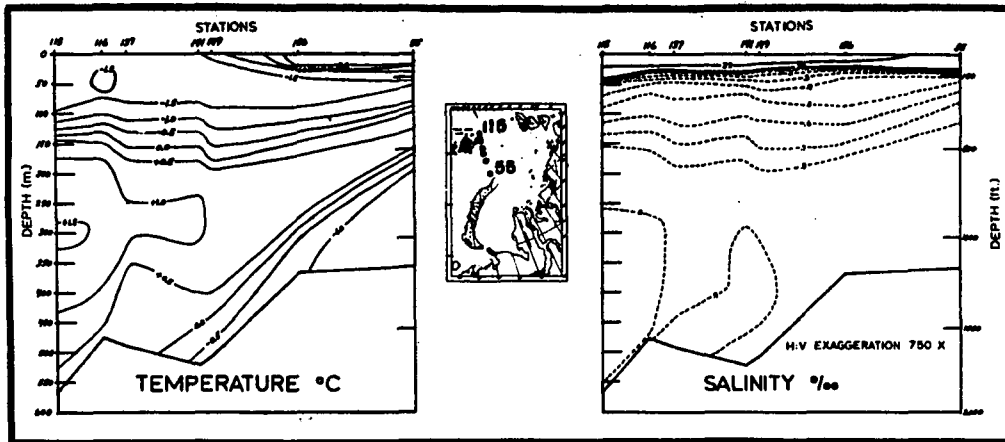


FIGURE A-21. Cross Sections of Temperature and Salinity Along Line T-T'

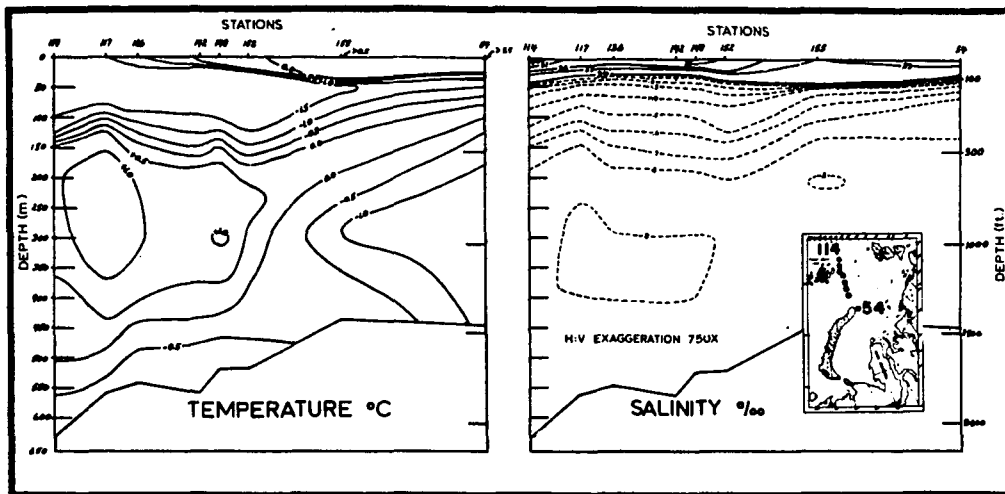


FIGURE A-22. Cross Sections of Temperature and Salinity Along Line U-U'

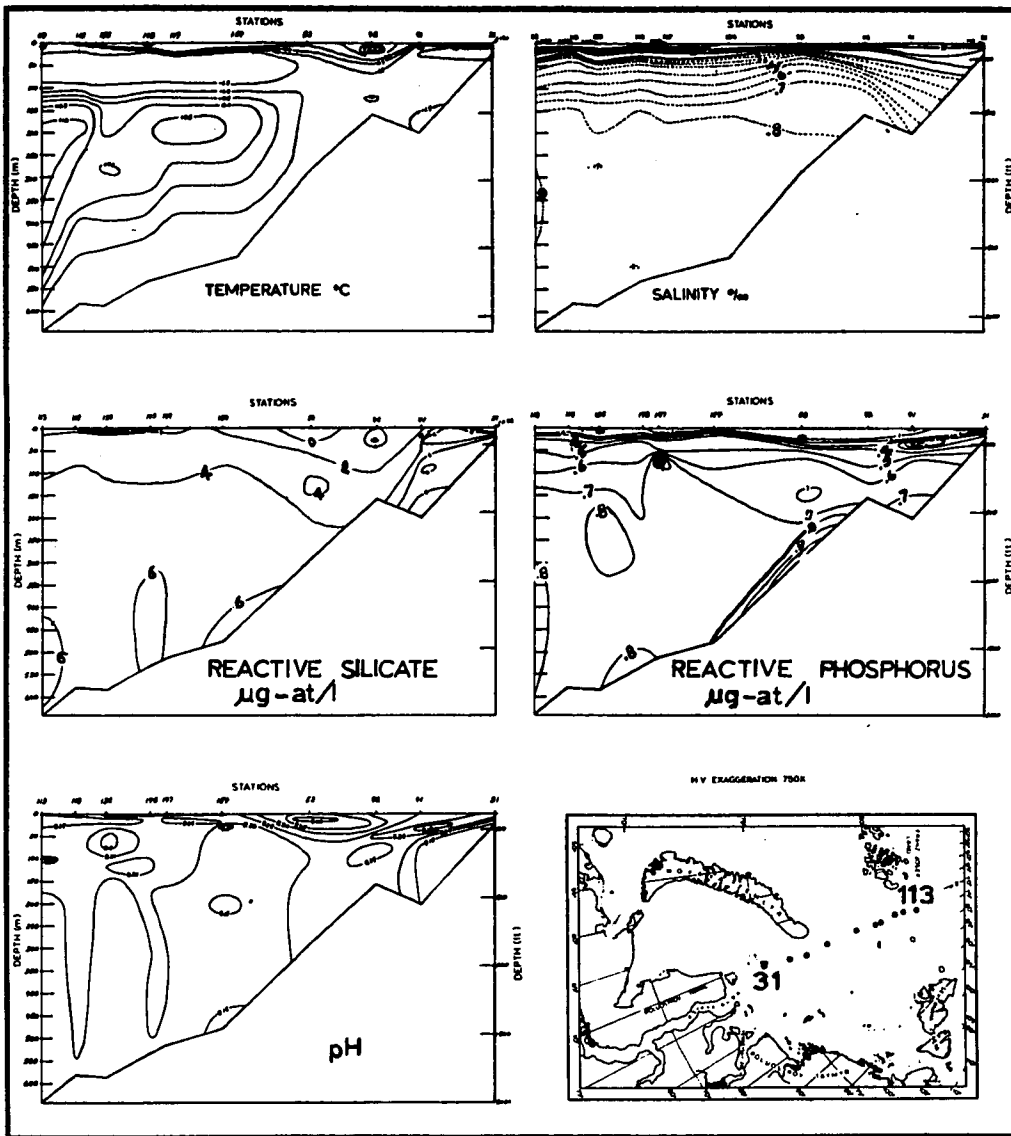


FIGURE A-23. Cross Sections of Temperature, Salinity, Reactive Silicate, Reactive Phosphorus, and pH Along Line V-V'

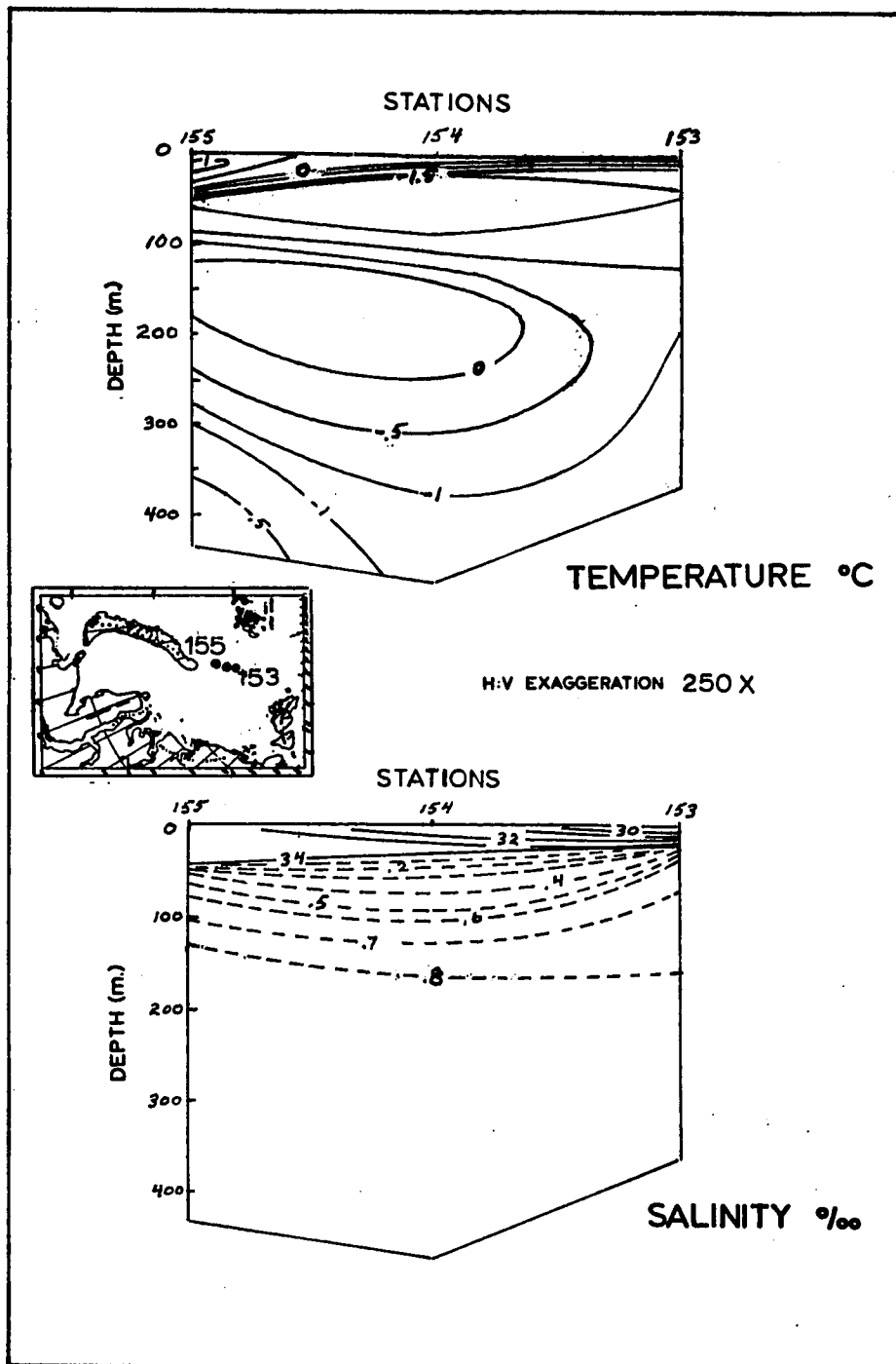


FIGURE A-24. Cross Sections of Temperature and Salinity Along Line W-W'

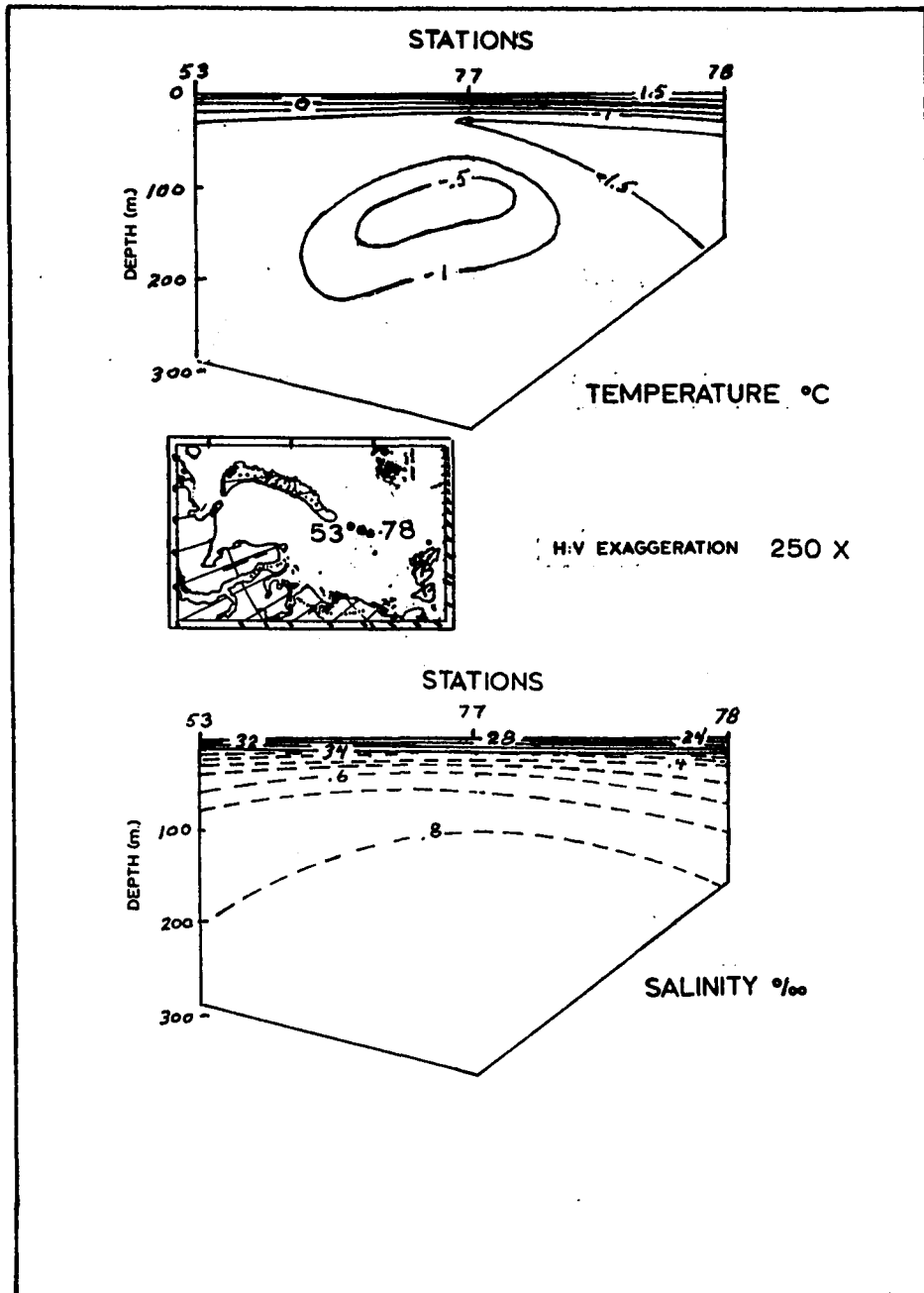


FIGURE A-25. Cross Sections of Temperature and Salinity Along Line X-X'

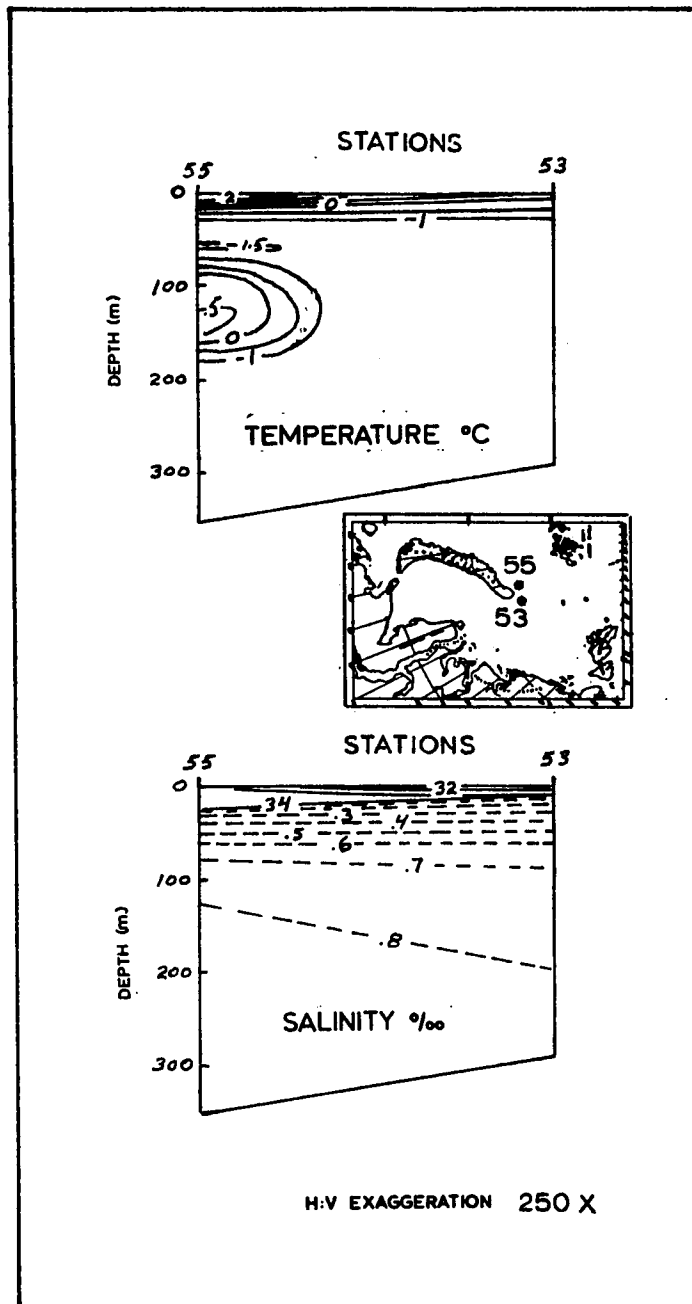


FIGURE A-26. Cross Sections of Temperature and Salinity along Line Y-Y'

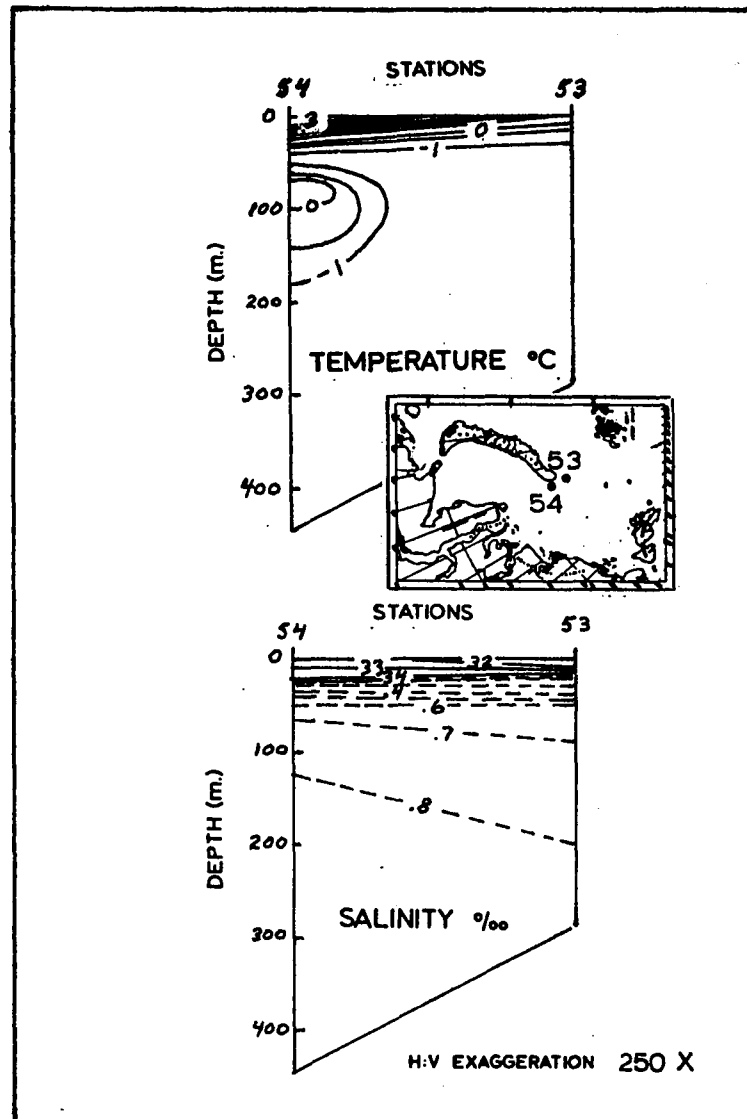


FIGURE 27. Cross Sections of Temperature and Salinity Along Line Z-Z'

APPENDIX B

AREAL DISTRIBUTIONS OF THE
PRINCIPAL KARA SEA PARAMETERS:

TEMPERATURE, SALINITY,
REACTIVE SILICATE, DISSOLVED OXYGEN,
REACTIVE PHOSPHORUS, AND pH

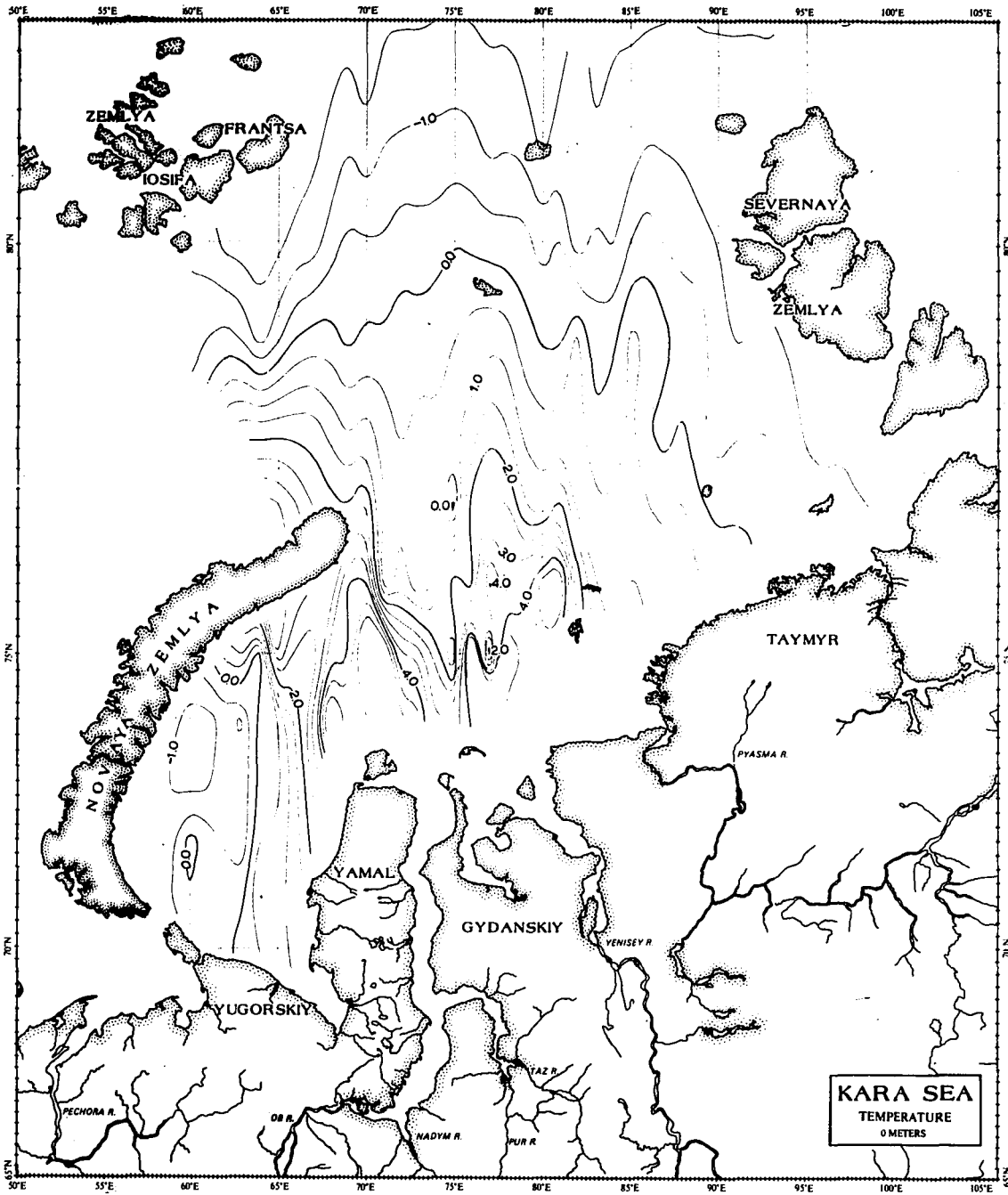


Figure B-1. Temperature distribution in the Kara Sea at the surface. C.I. 0.5°C

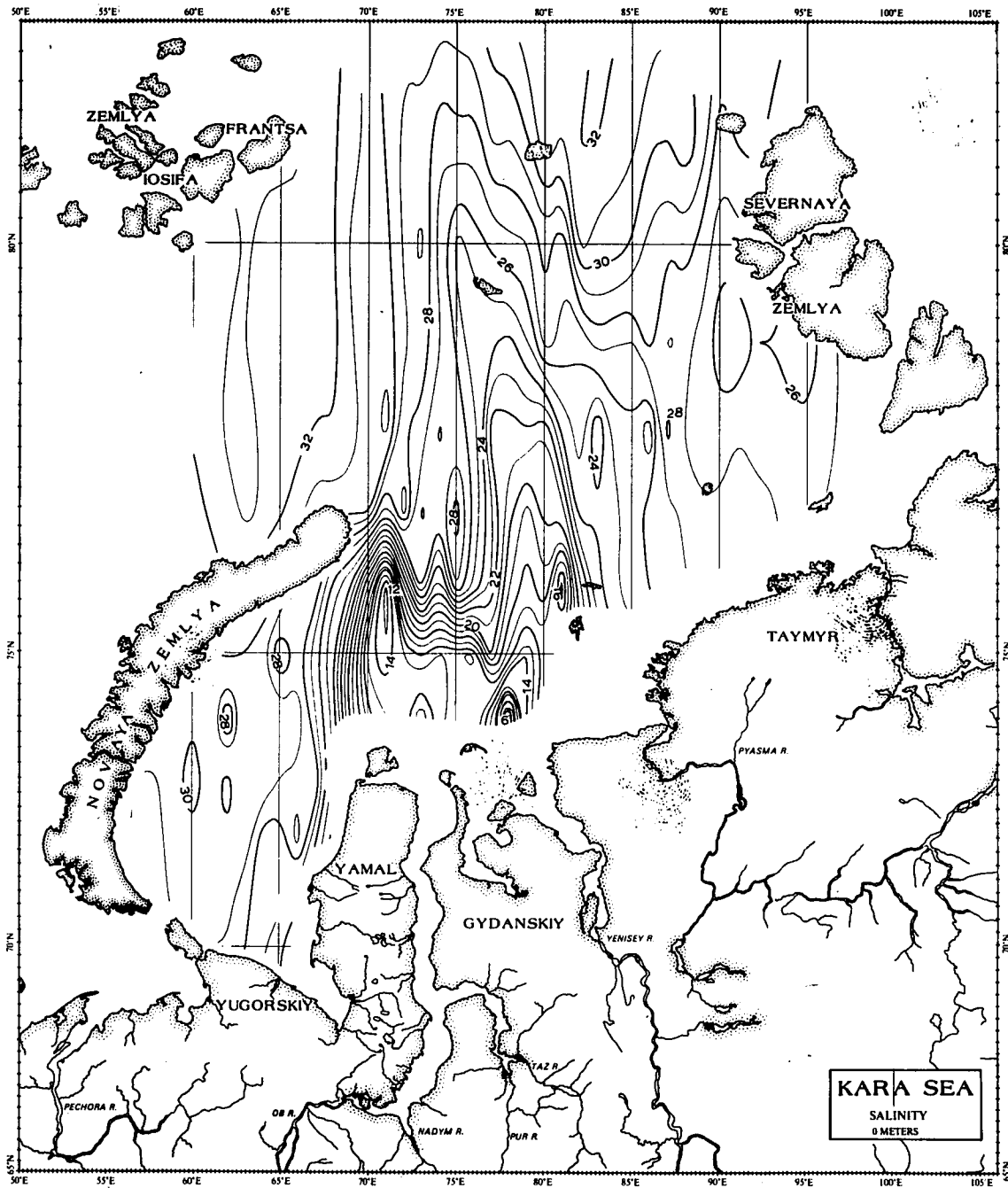


Figure B-2. Salinity distribution in the Kara Sea at the surface. C.I. 1 ‰

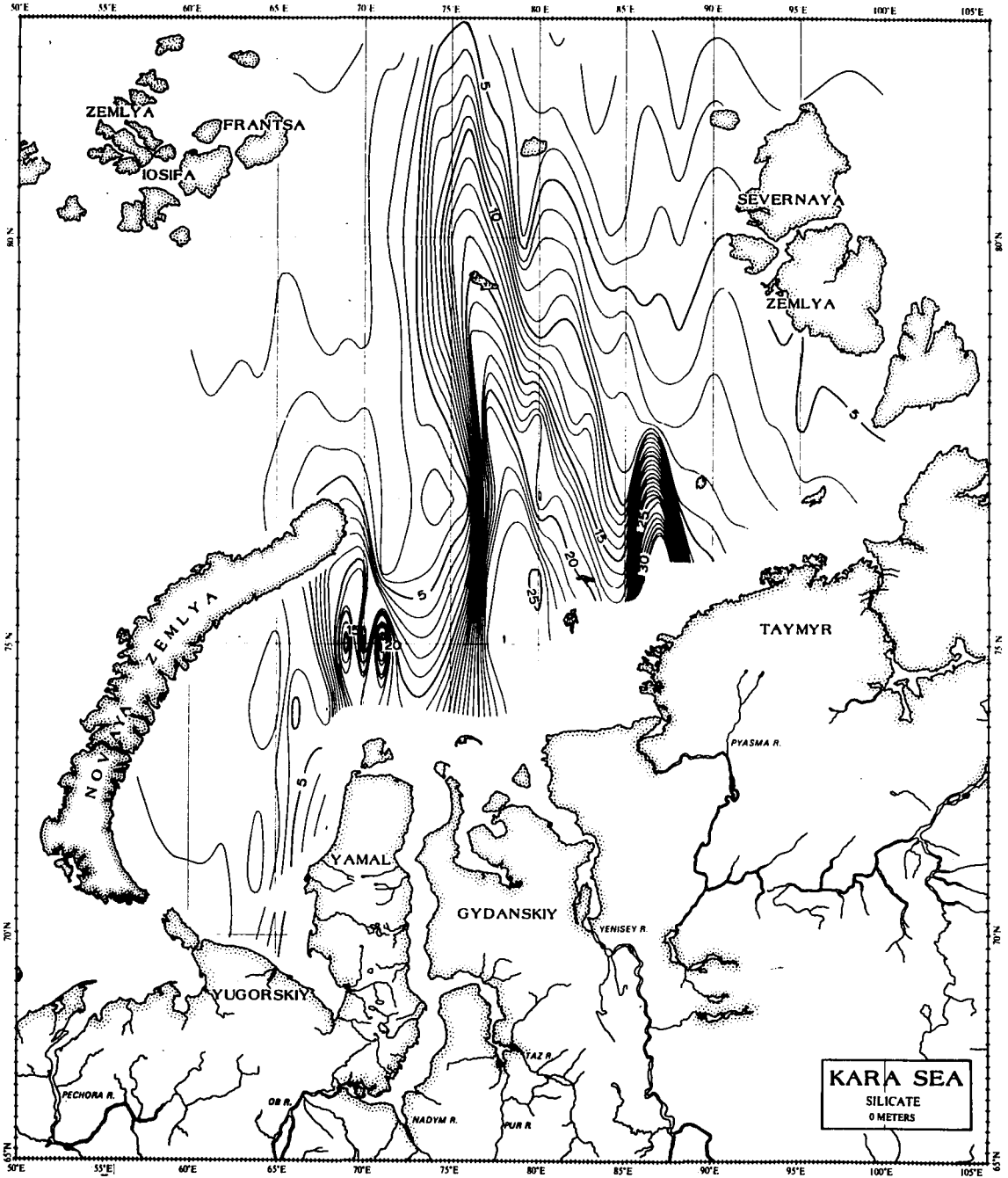


Figure B-3. Reactive silicate distribution in the Kara Sea at the surface. C.I. $1 \mu\text{g-at/l}$

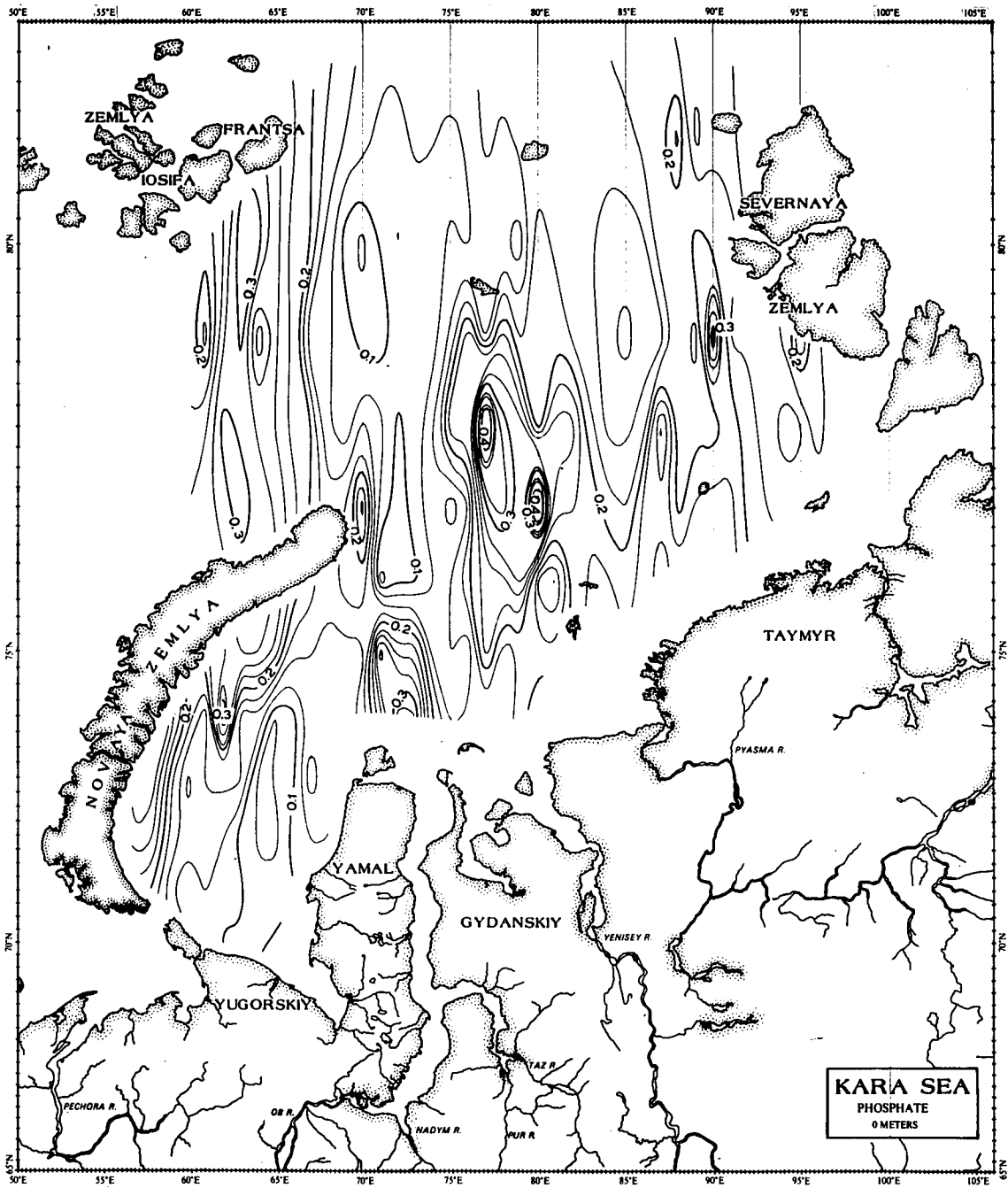


Figure B-4. Reactive phosphorus distribution in the Kara Sea at the surface. C.I. $0.025 \mu\text{g-at/l}$

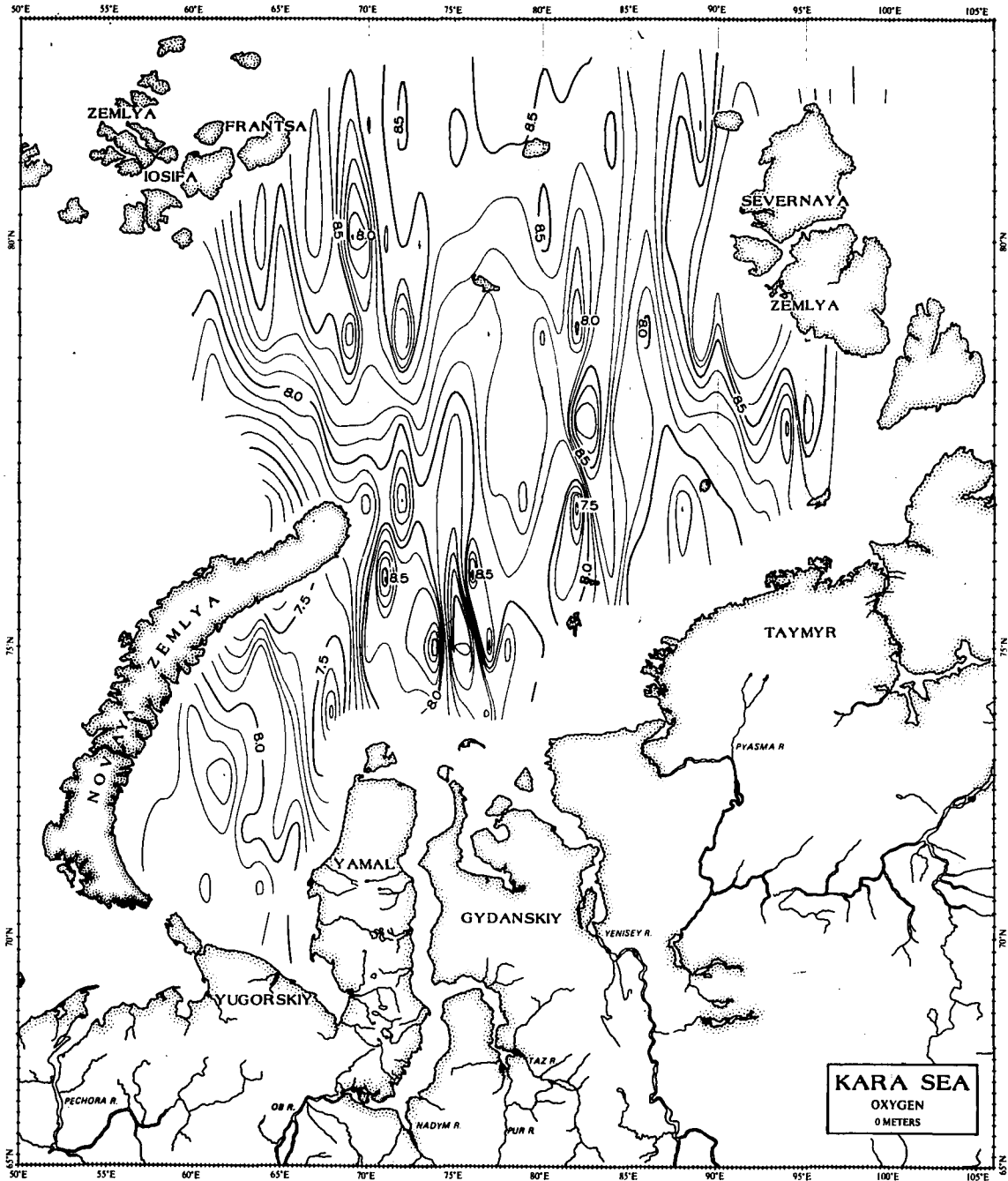


Figure B-5. Dissolved oxygen distribution in the Kara Sea at the surface. C.I. 0.1 ml/l

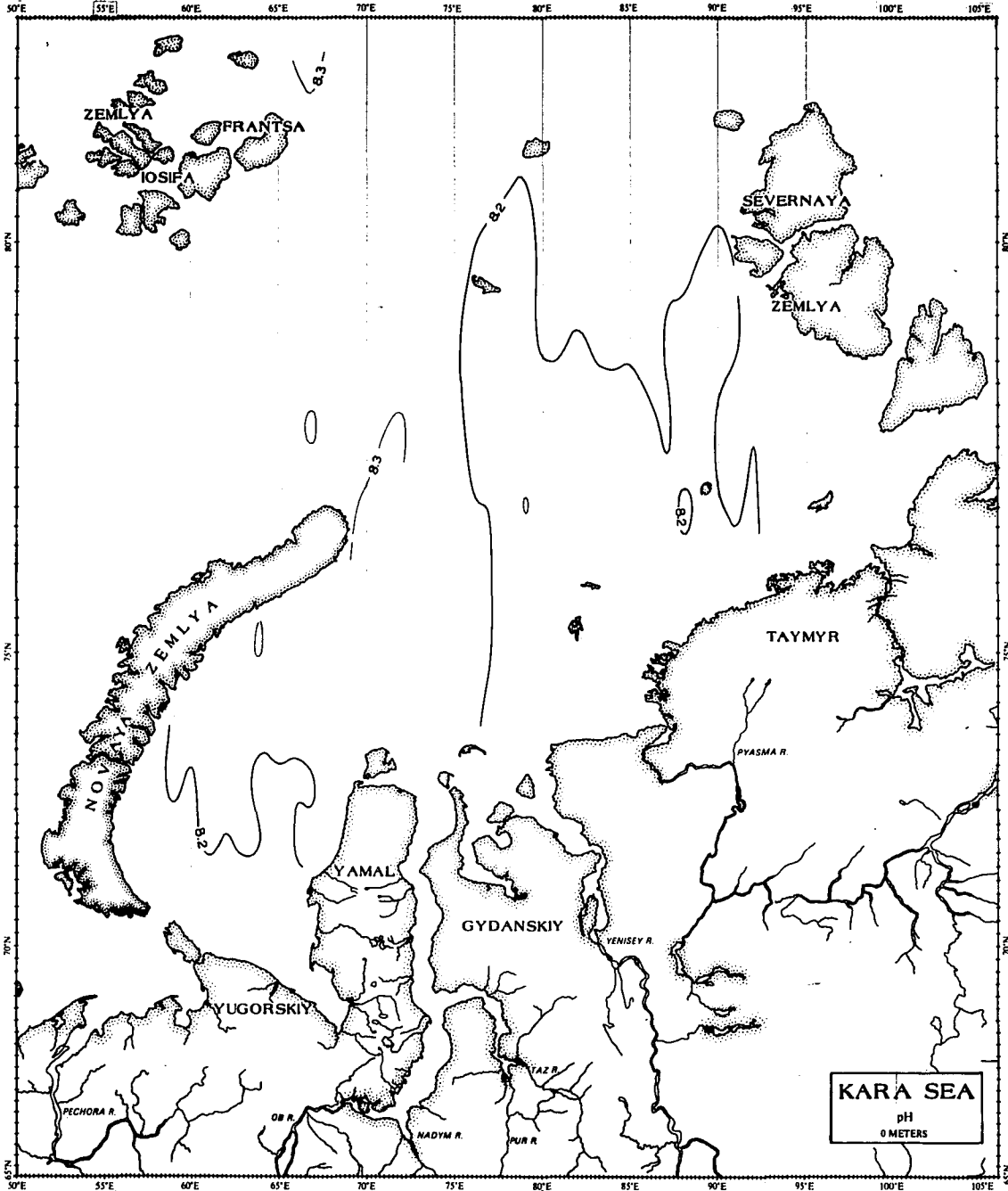


Figure B-6. pH distribution in the Kara Sea at the surface. C.I. 0.1

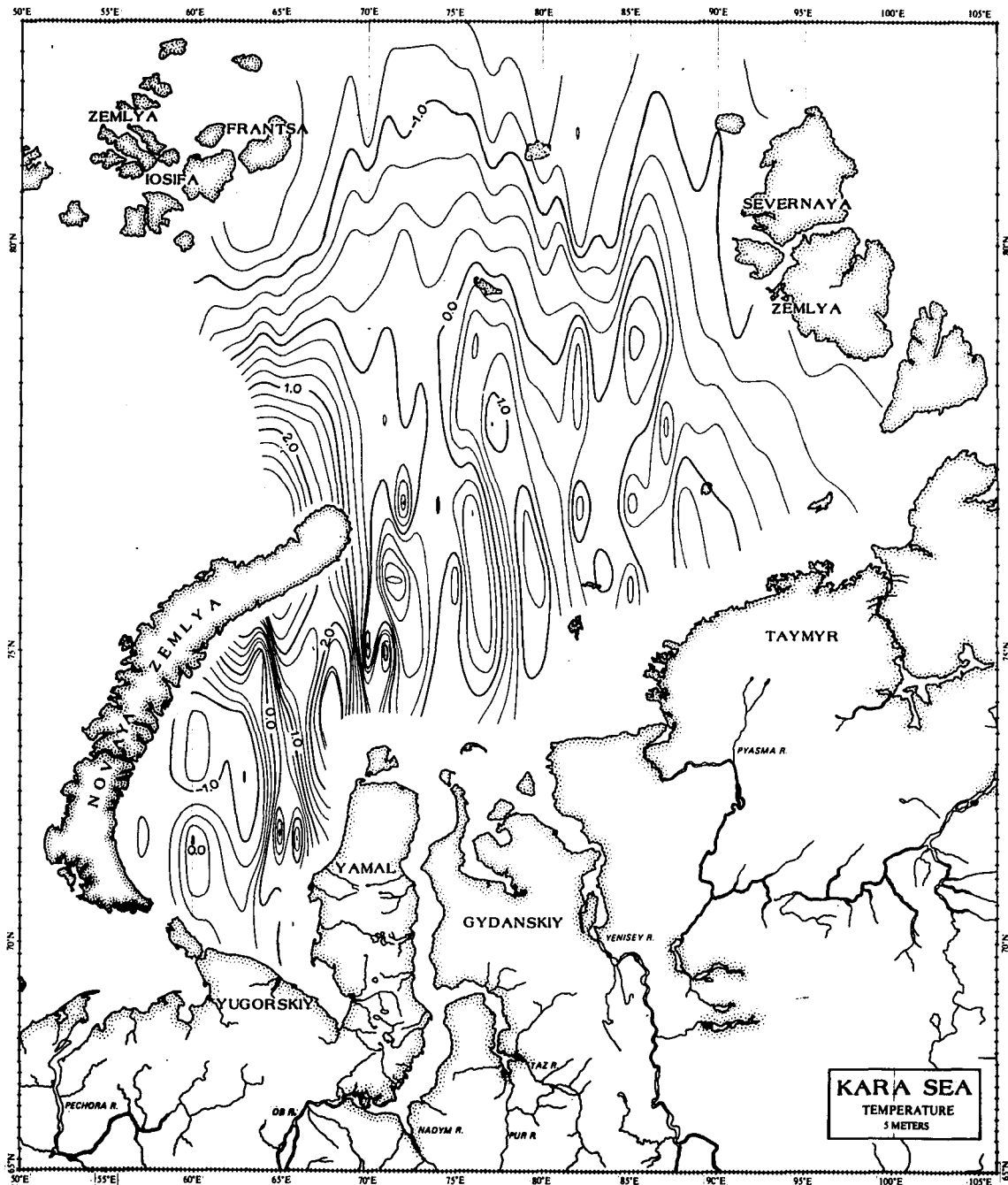


Figure B-7. Temperature distribution in the Kara Sea at 5 meters. C.I. 0.25°C

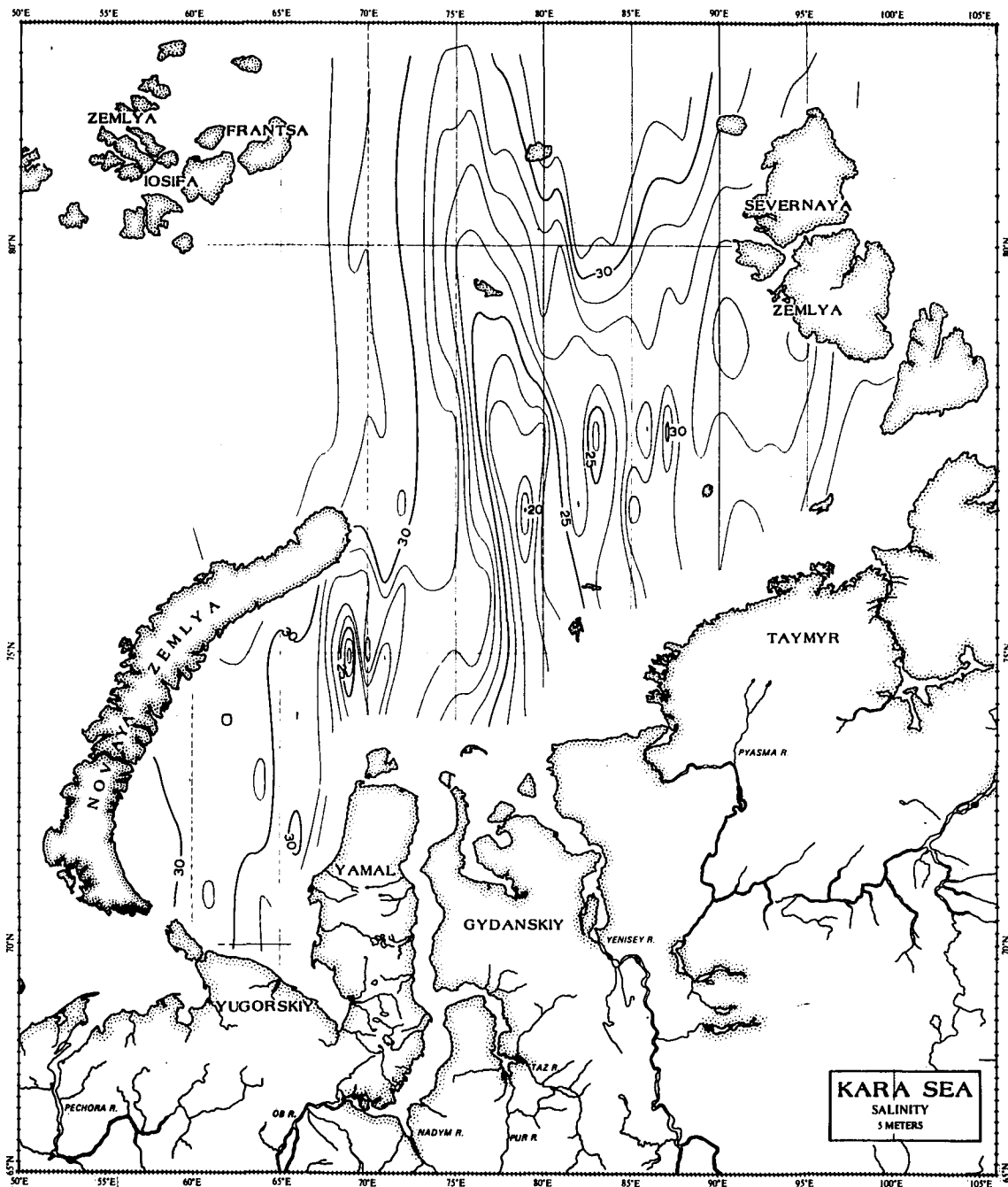


Figure B-8. Salinity distribution in the Kara Sea at 5 meters. C.I. 1 ‰

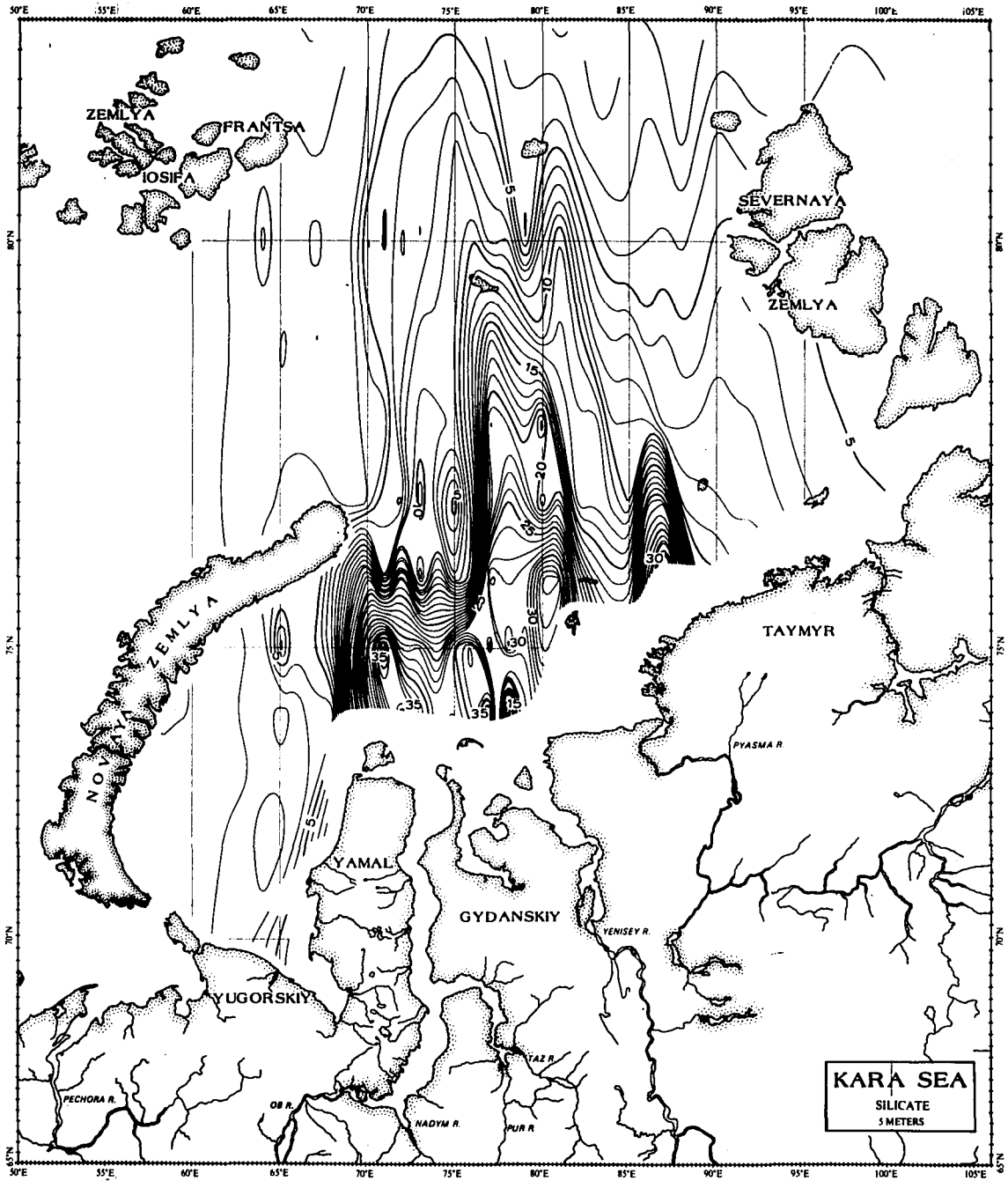


Figure B-9. Reactive silicate distribution in the Kara Sea at 5 meters. C.I. $1 \mu\text{g-at/l}$

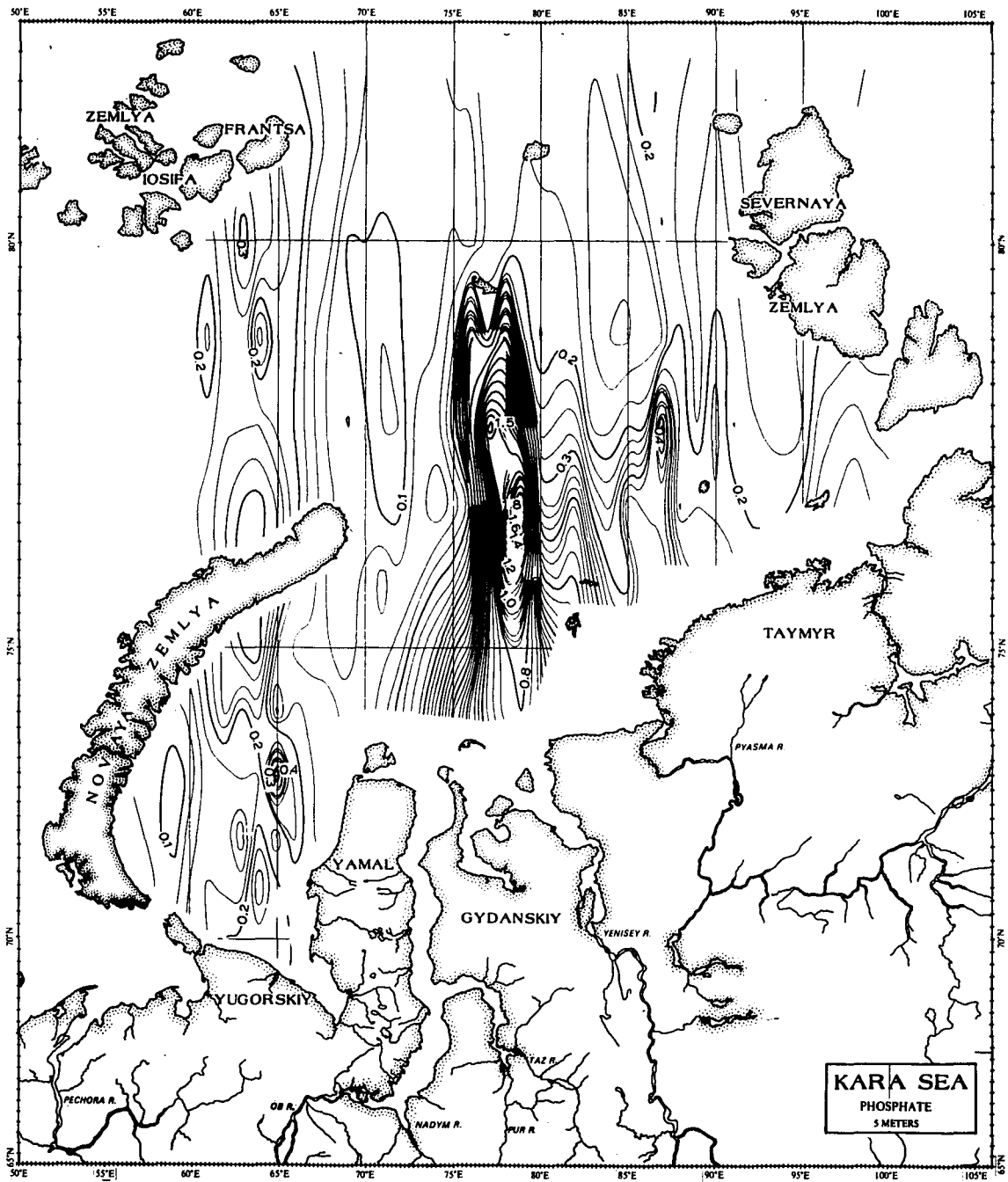


Figure B-10. Reactive phosphorus distribution in the Kara Sea at 5 meters. C.I. $0.025 \mu\text{g-at/l}$

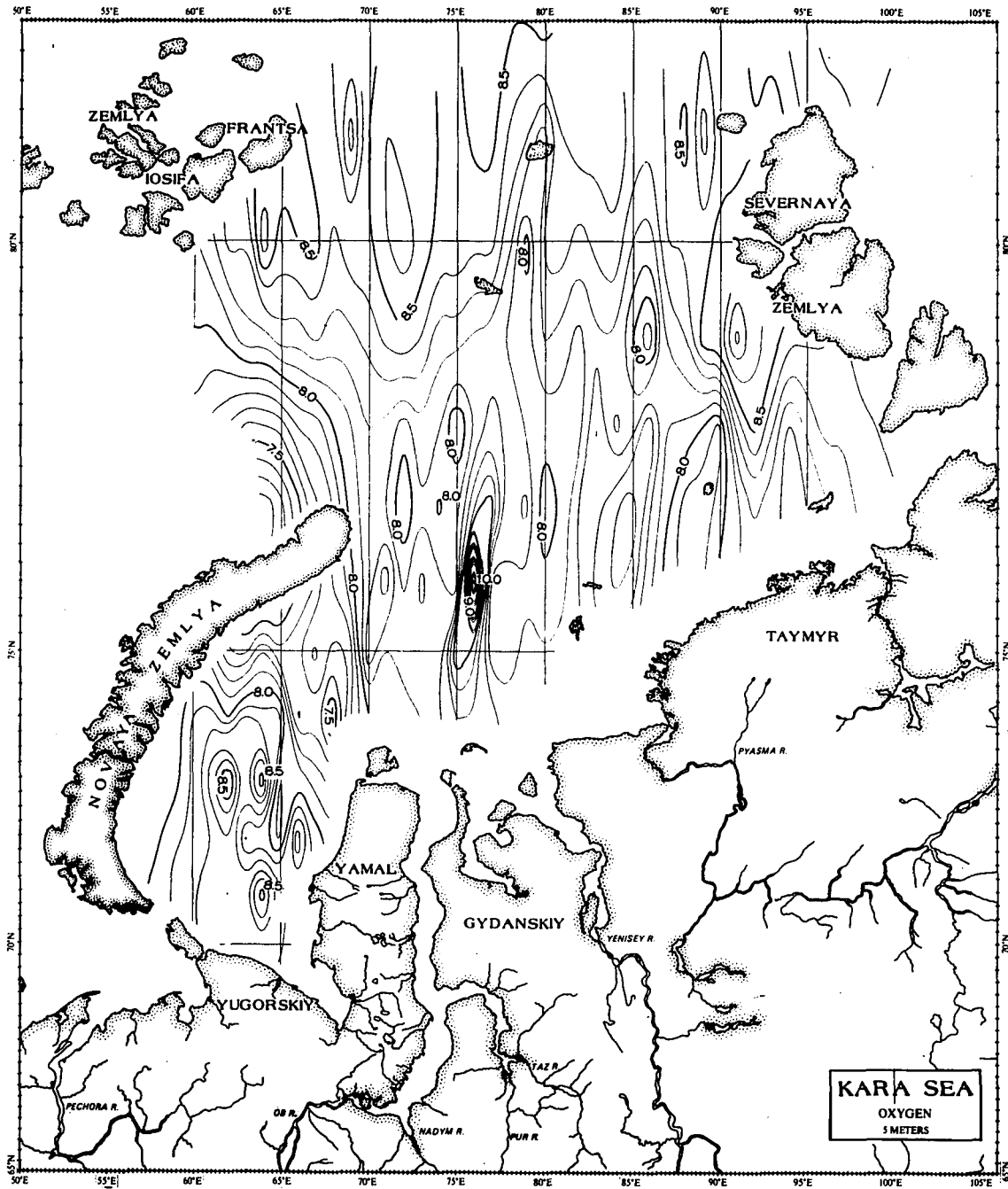


Figure B-11. Dissolved oxygen distribution in the Kara Sea at 5 meters. C.I. 0.1 ml/l

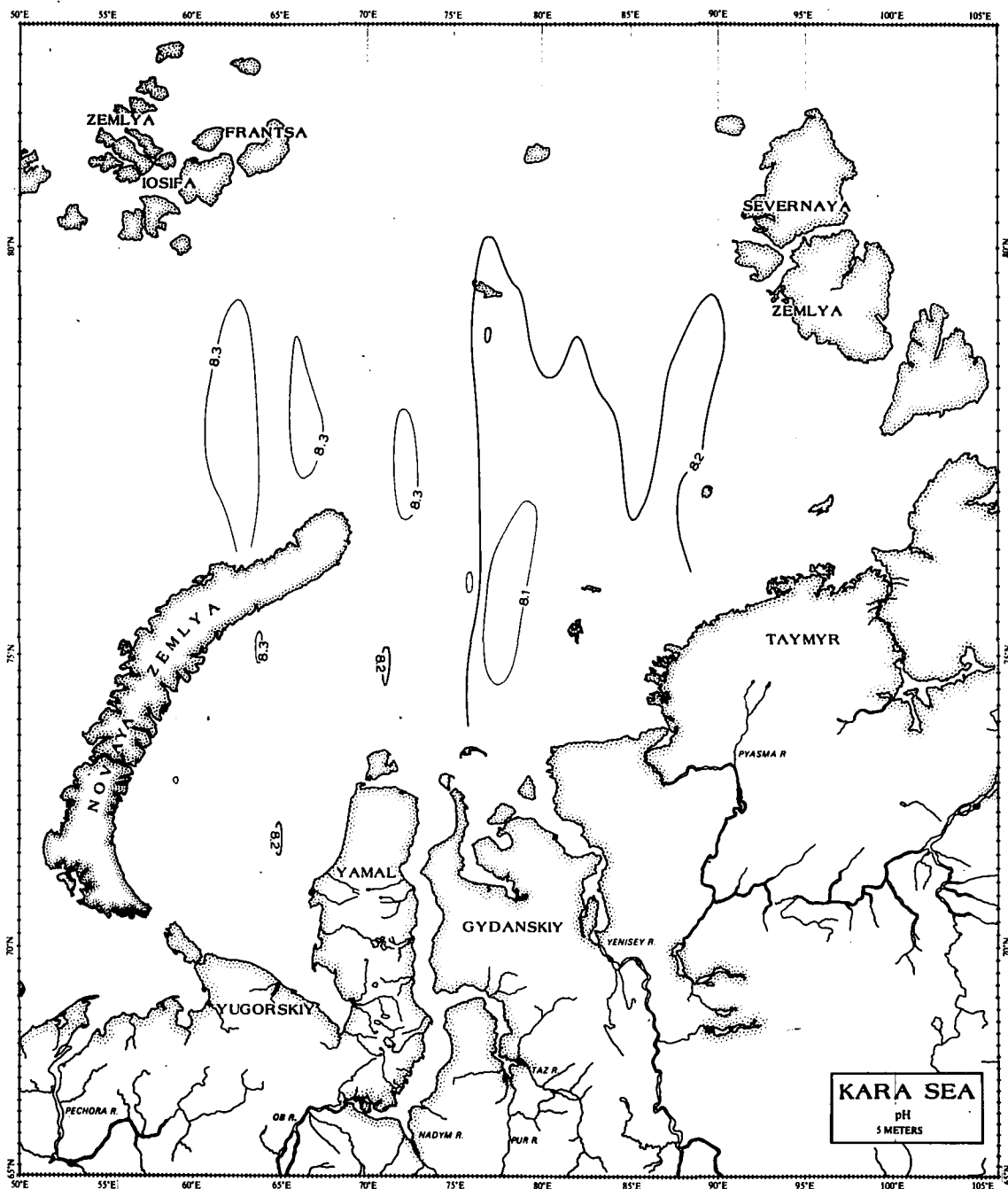


Figure B-12. pH distribution in the Kara Sea at 5 meters. C.I. 0.1

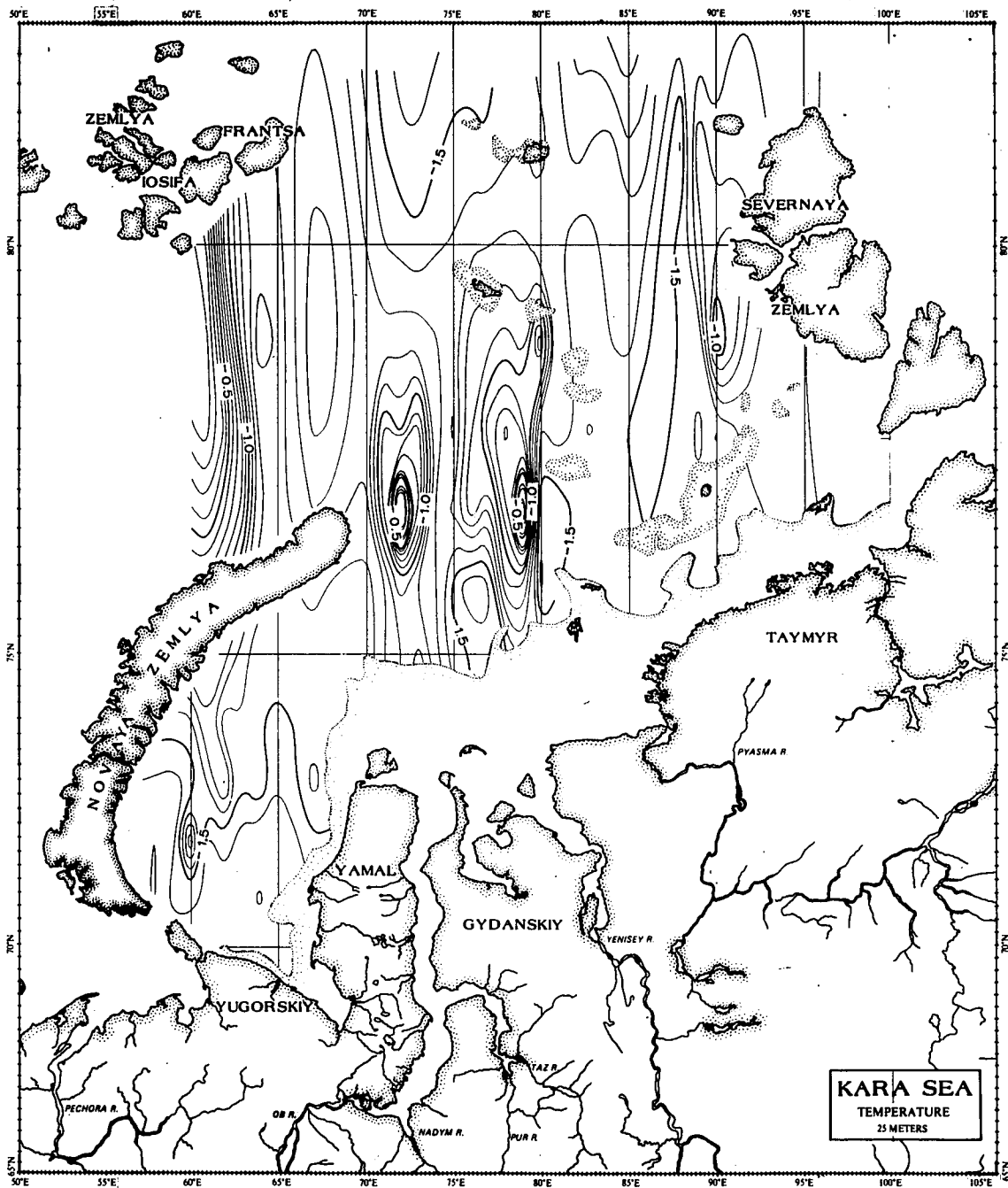


Figure B-13. Temperature distribution in the Kara Sea at 25 meters. C.I. 0.1°C

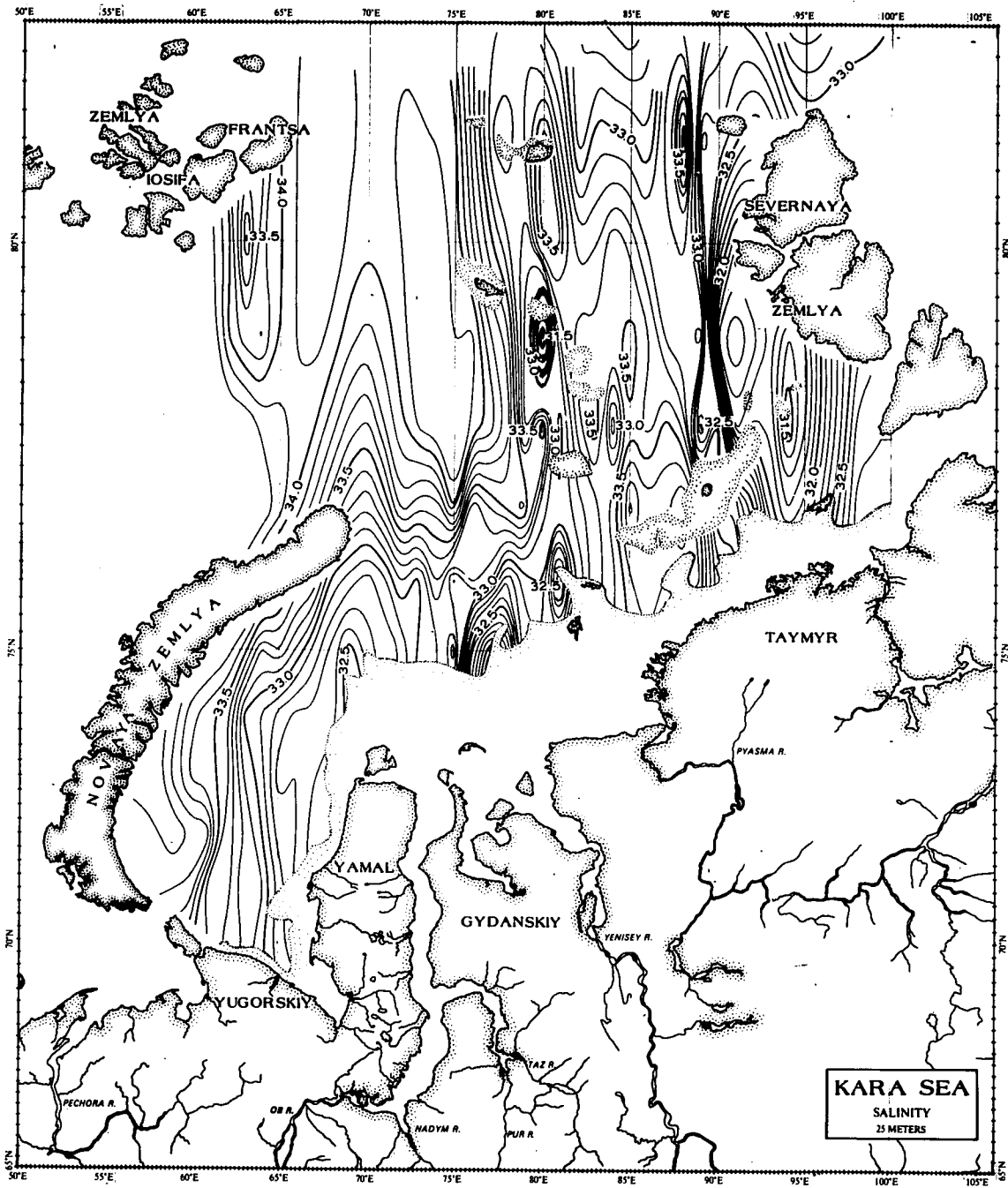


Figure B-14. Salinity distribution in the Kara Sea at 25 meters. C.I. 0.1 ‰

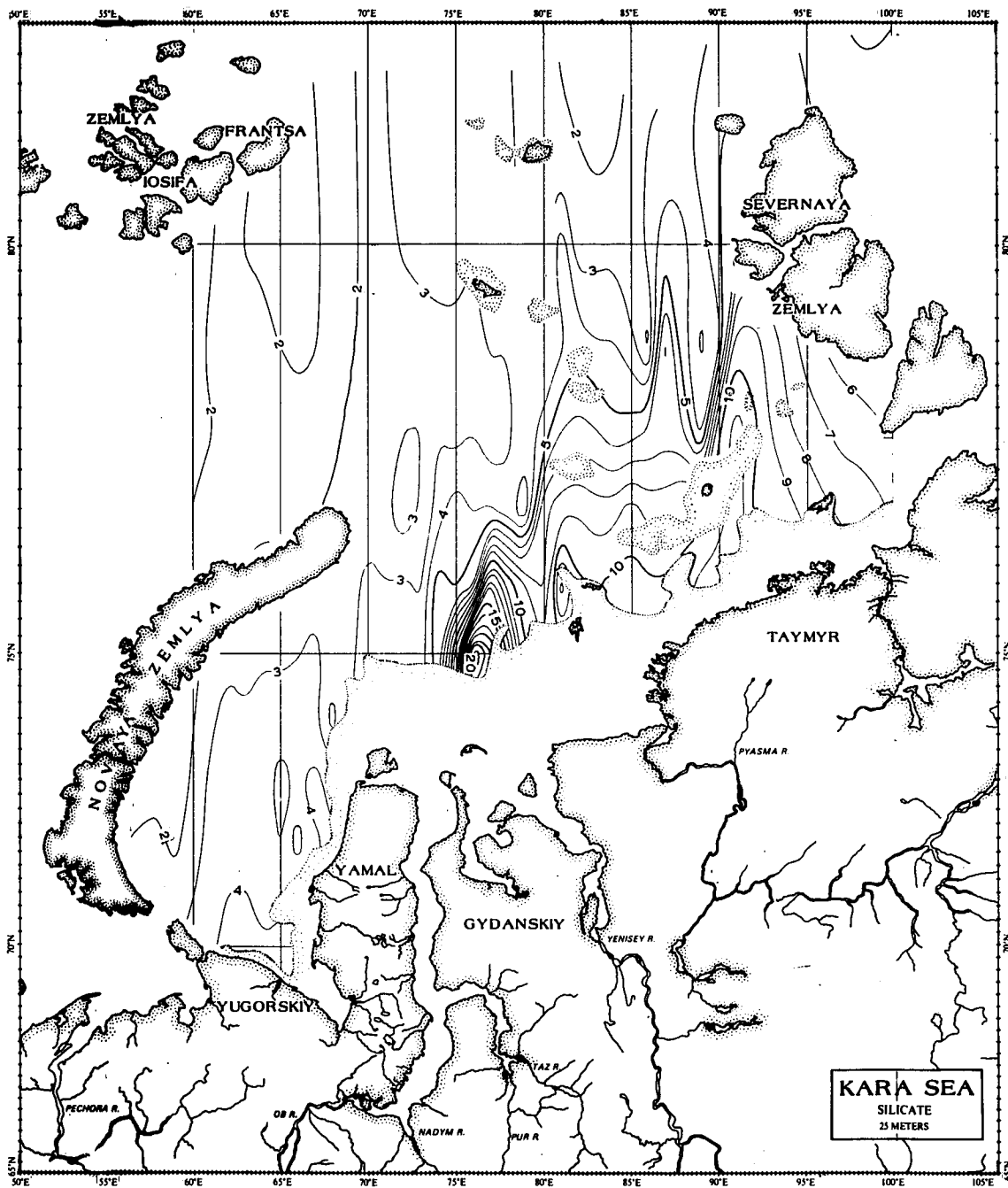


Figure B-15. Reactive silicate distribution in the Kara Sea at 25 meters. C.I. $1 \mu\text{g-at/l}$

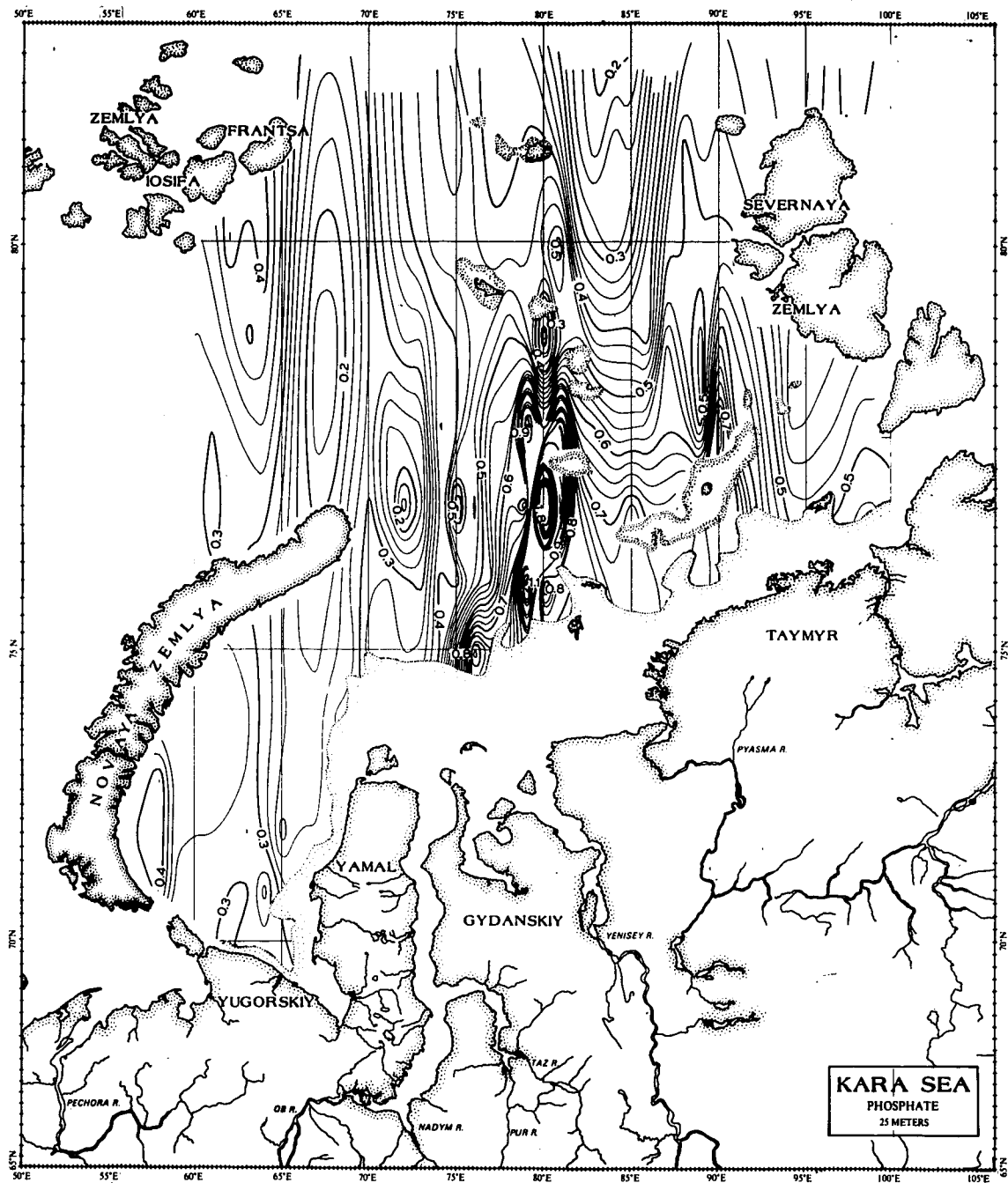


Figure B-16. Reactive phosphorus distribution in the Kara Sea at 25 meters. C.I. 0.025 $\mu\text{g-at/l}$

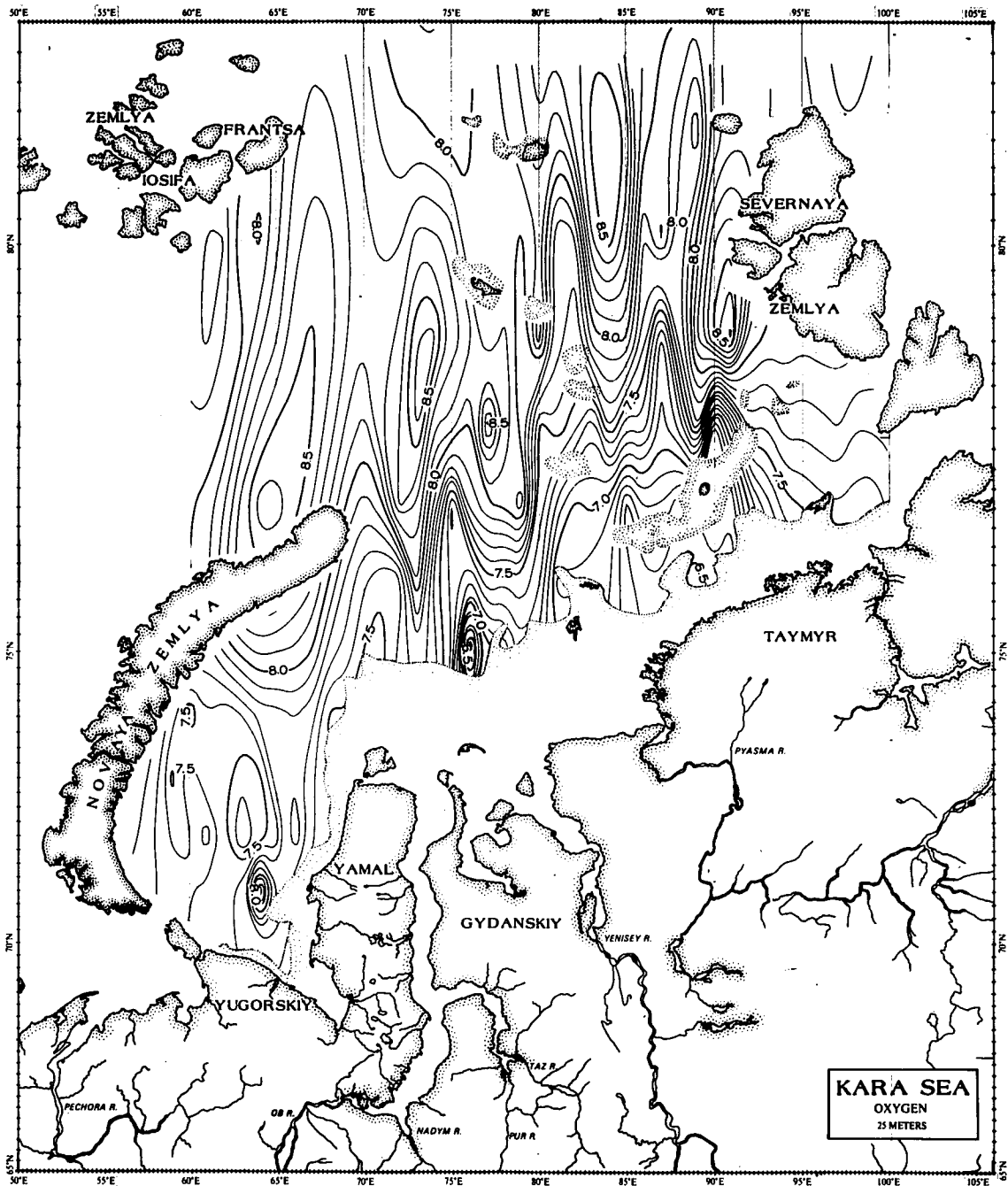


Figure B-17. Dissolved oxygen distribution in the Kara Sea at 25 meters. C.I. 0.1 ml/l

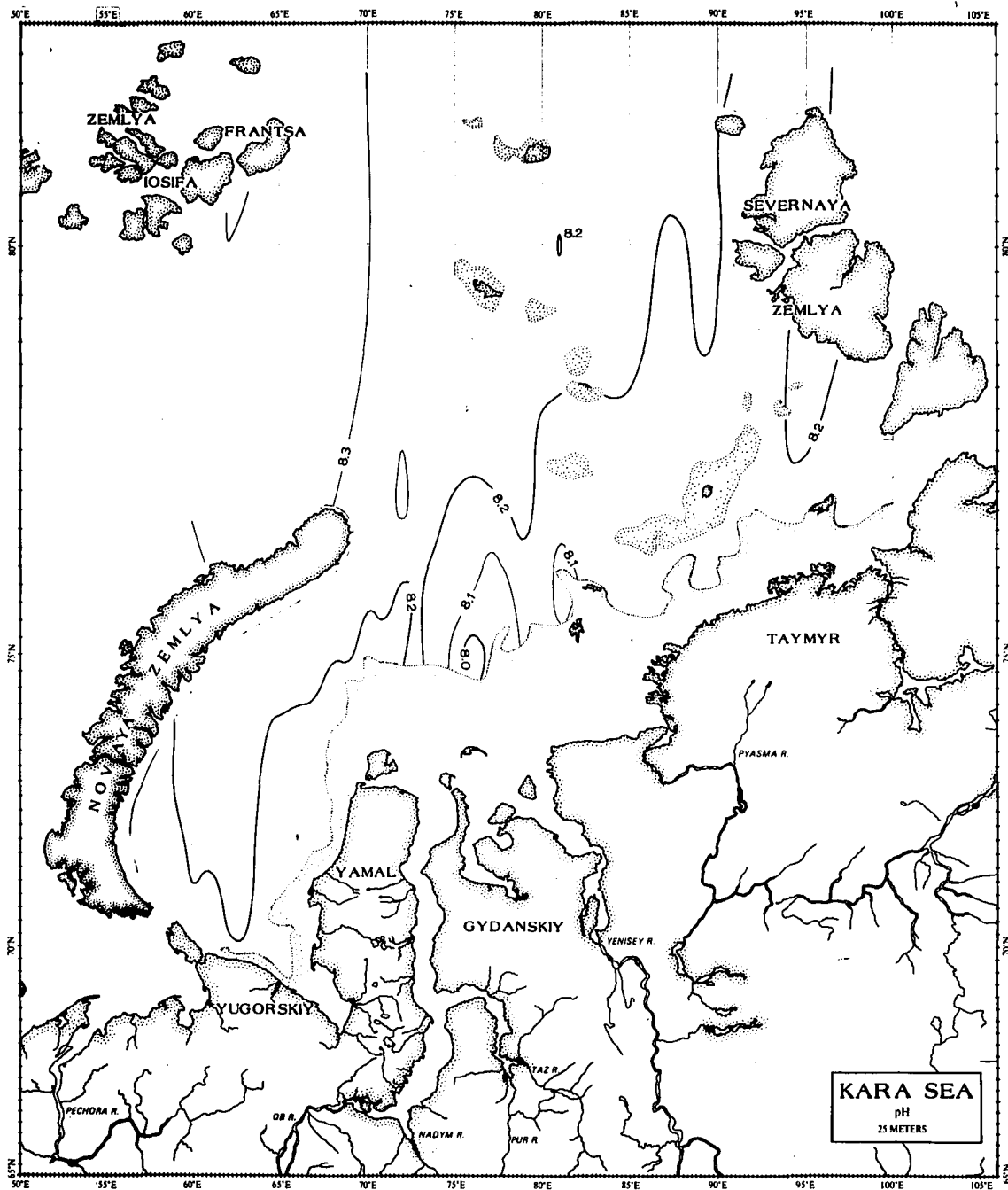


Figure B-18. pH distribution in the Kara Sea at 25 meters. C.I. 0.1

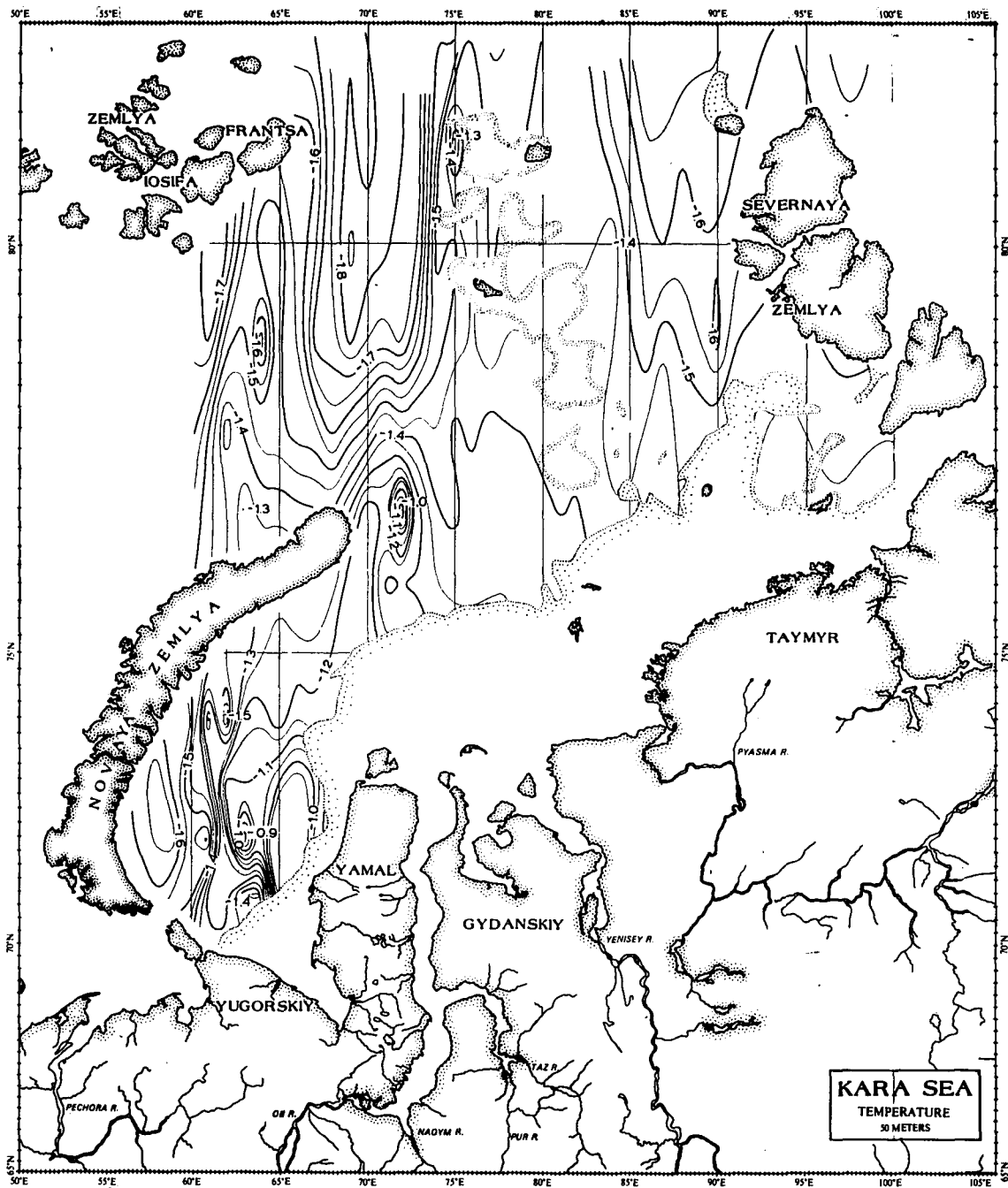


Figure B-19. Temperature distribution in the Kara Sea at 50 meters. C.I. 0.05°C

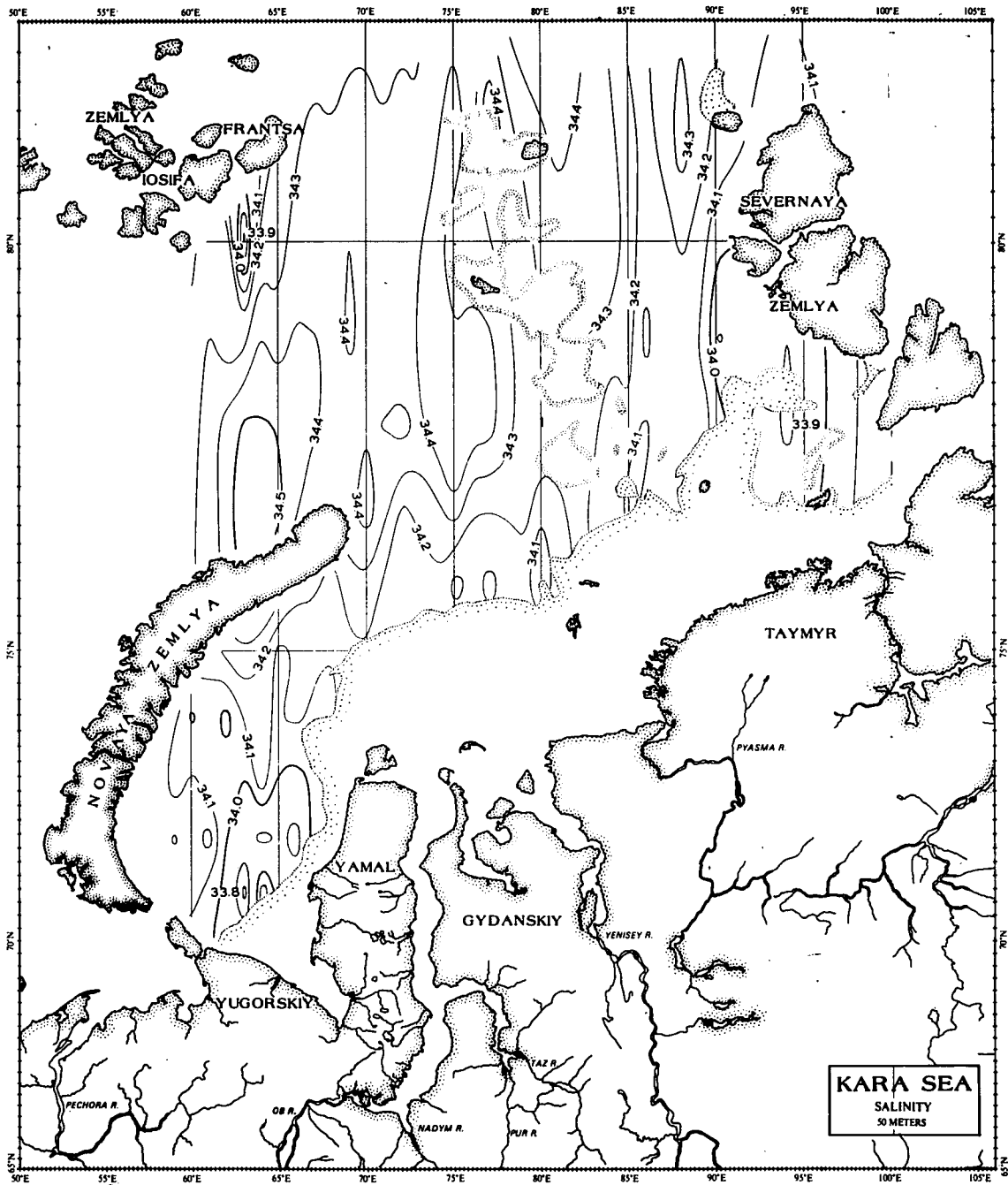


Figure B-20. Salinity distribution in the Kara Sea at 50 meters. C.I. 0.1 ‰

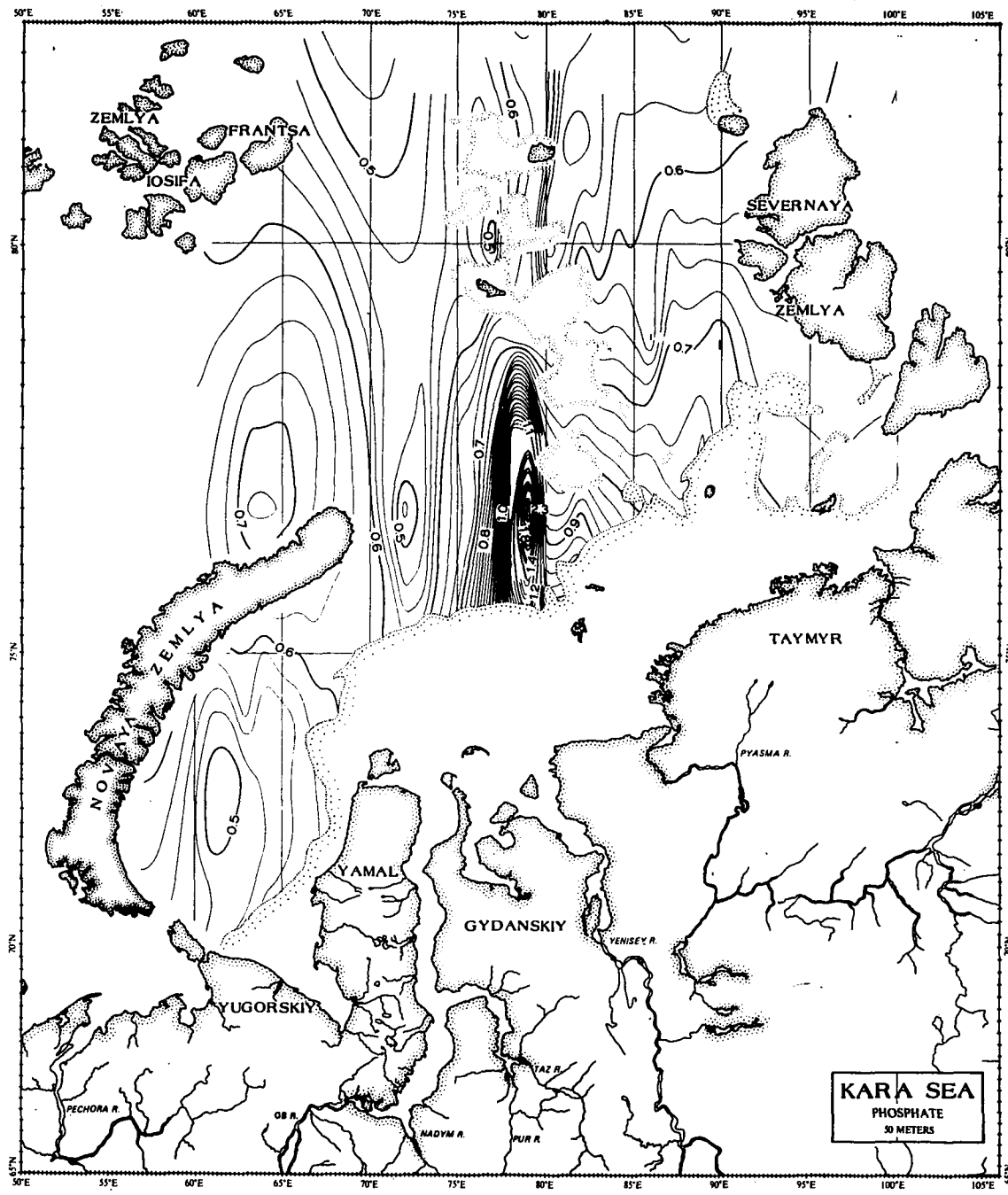


Figure B-21. Reactive phosphorus distribution in the Kara Sea at 50 meters. C.I. 0.025 $\mu\text{g-at/l}$

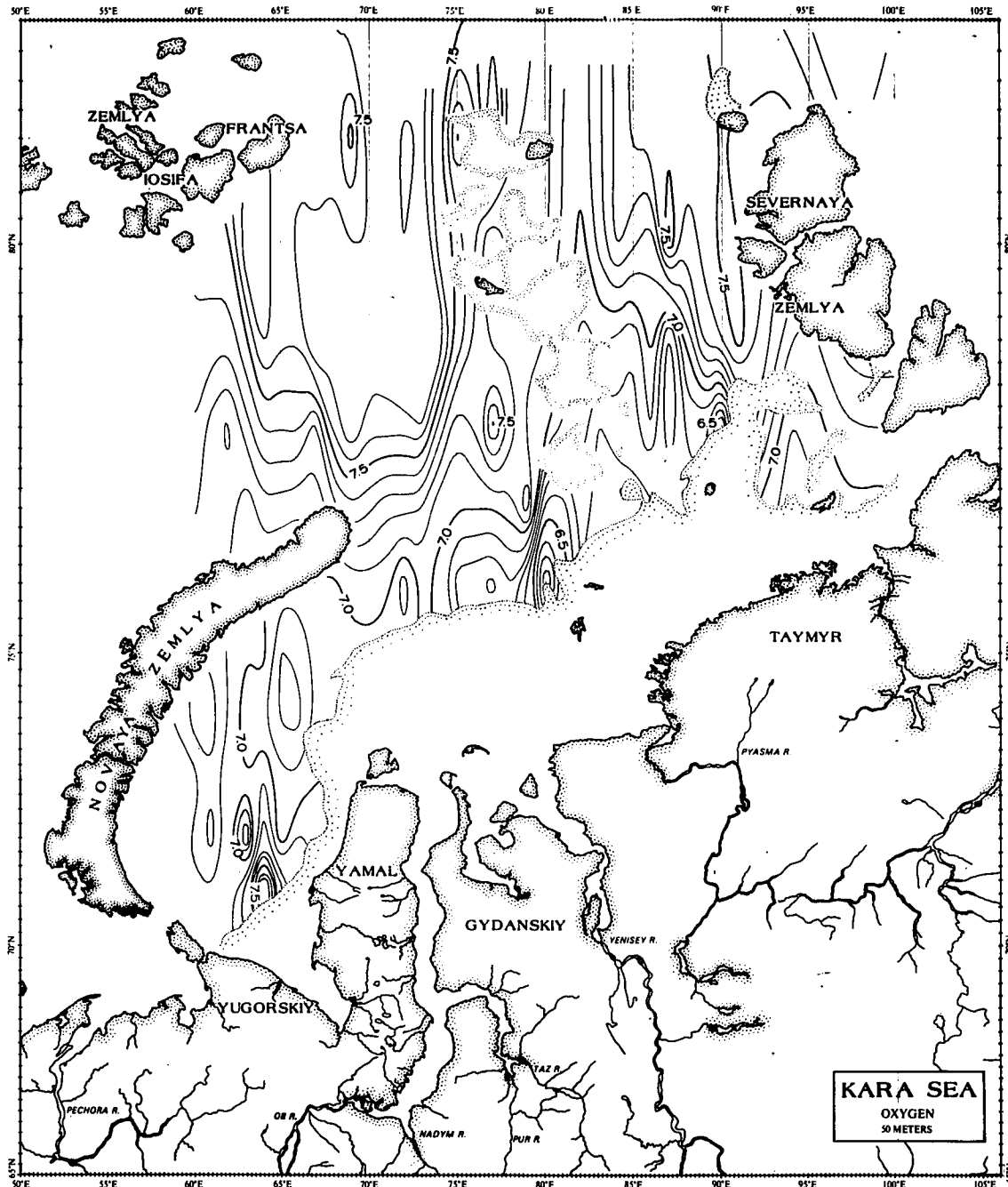


Figure B-22. Dissolved oxygen distribution in the Kara Sea at 50 meters. C.I. 0.1 ml/l

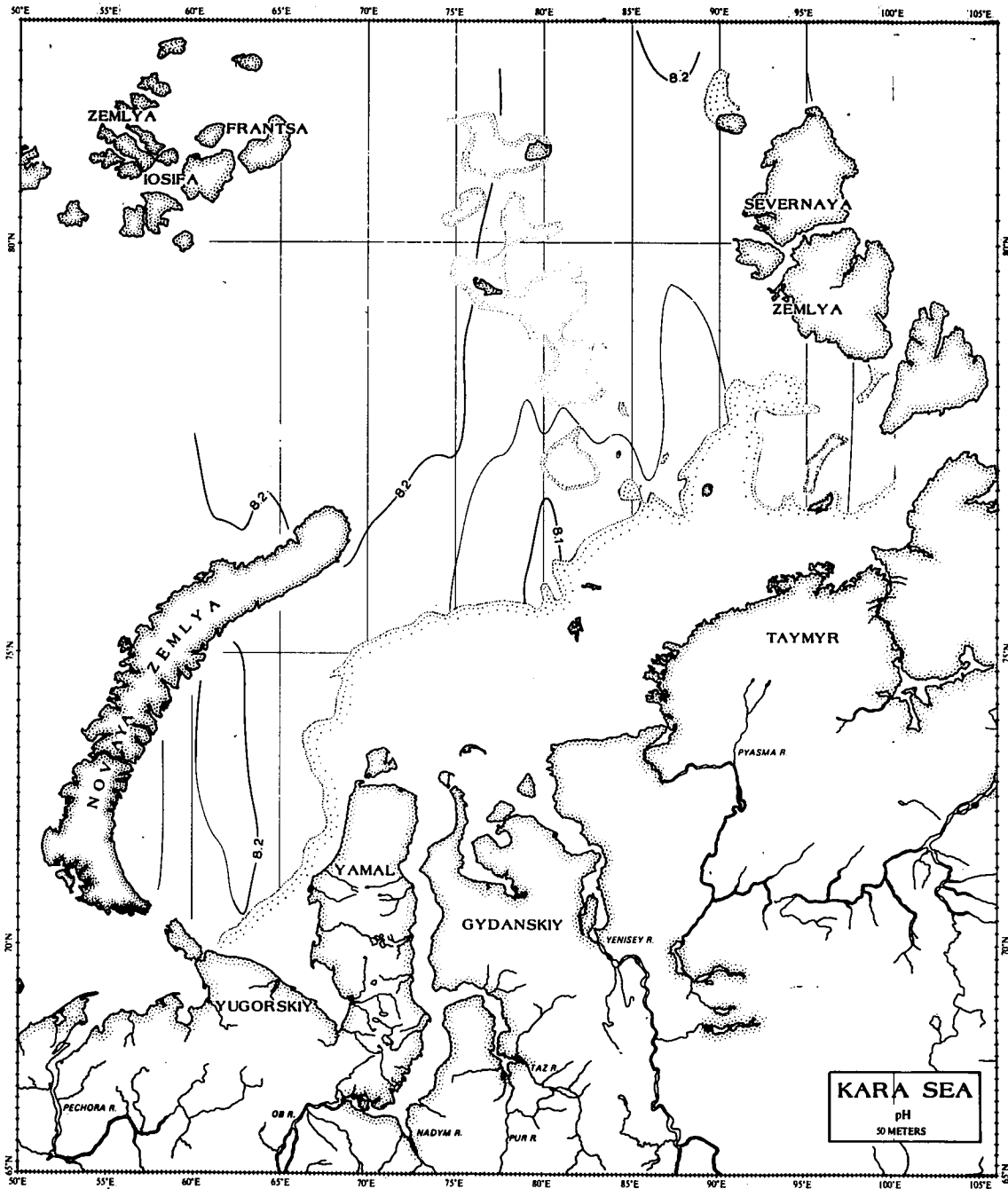


Figure B-23. pH distribution in the Kara Sea at 50 meters. C.I. 0.05

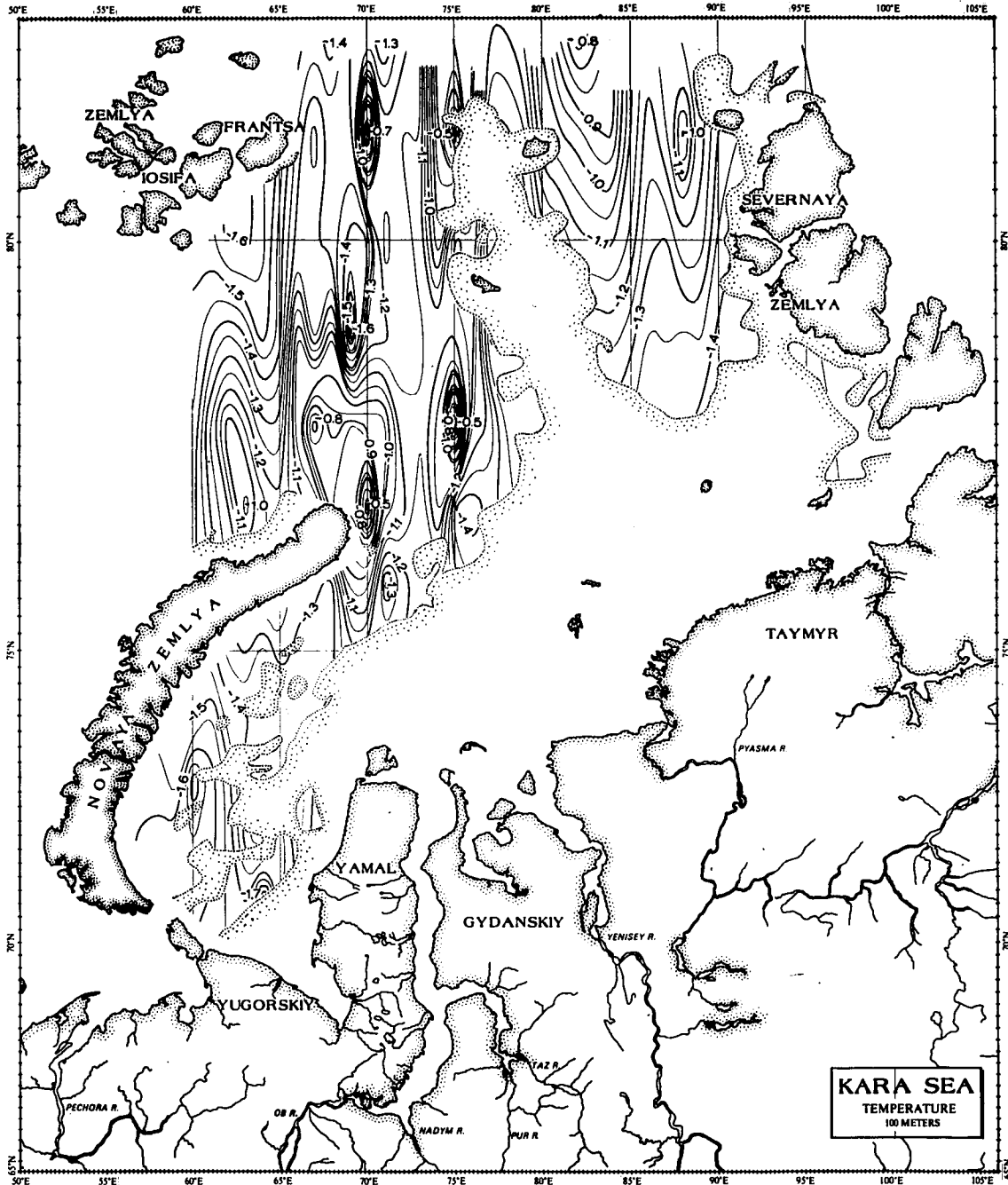


Figure B-24. Temperature distribution in the Kara Sea at 100 meters. C.I. 0.05 C

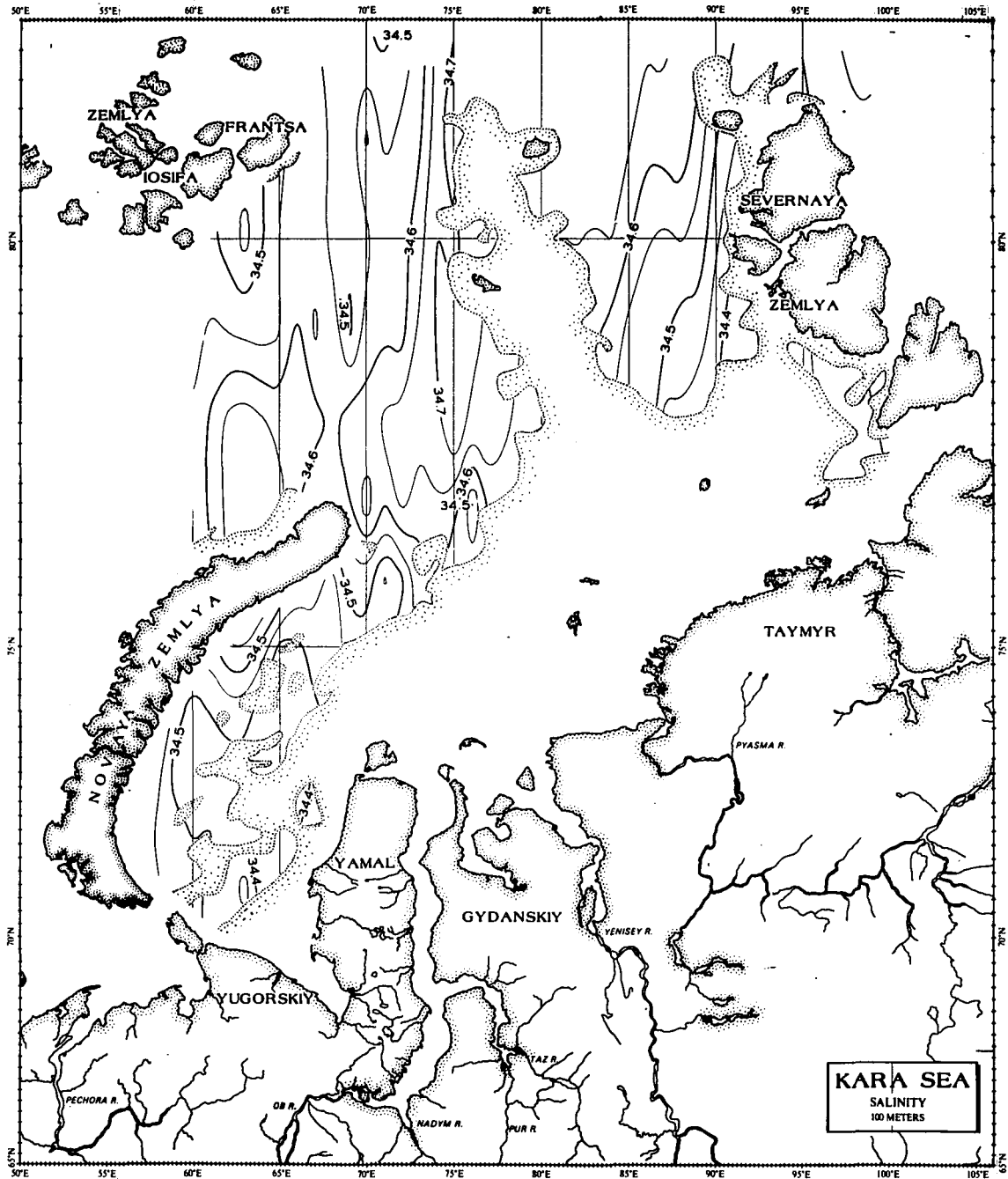


Figure B-25. Salinity distribution in the Kara Sea at 100 meters. C.I. 0.05 ‰

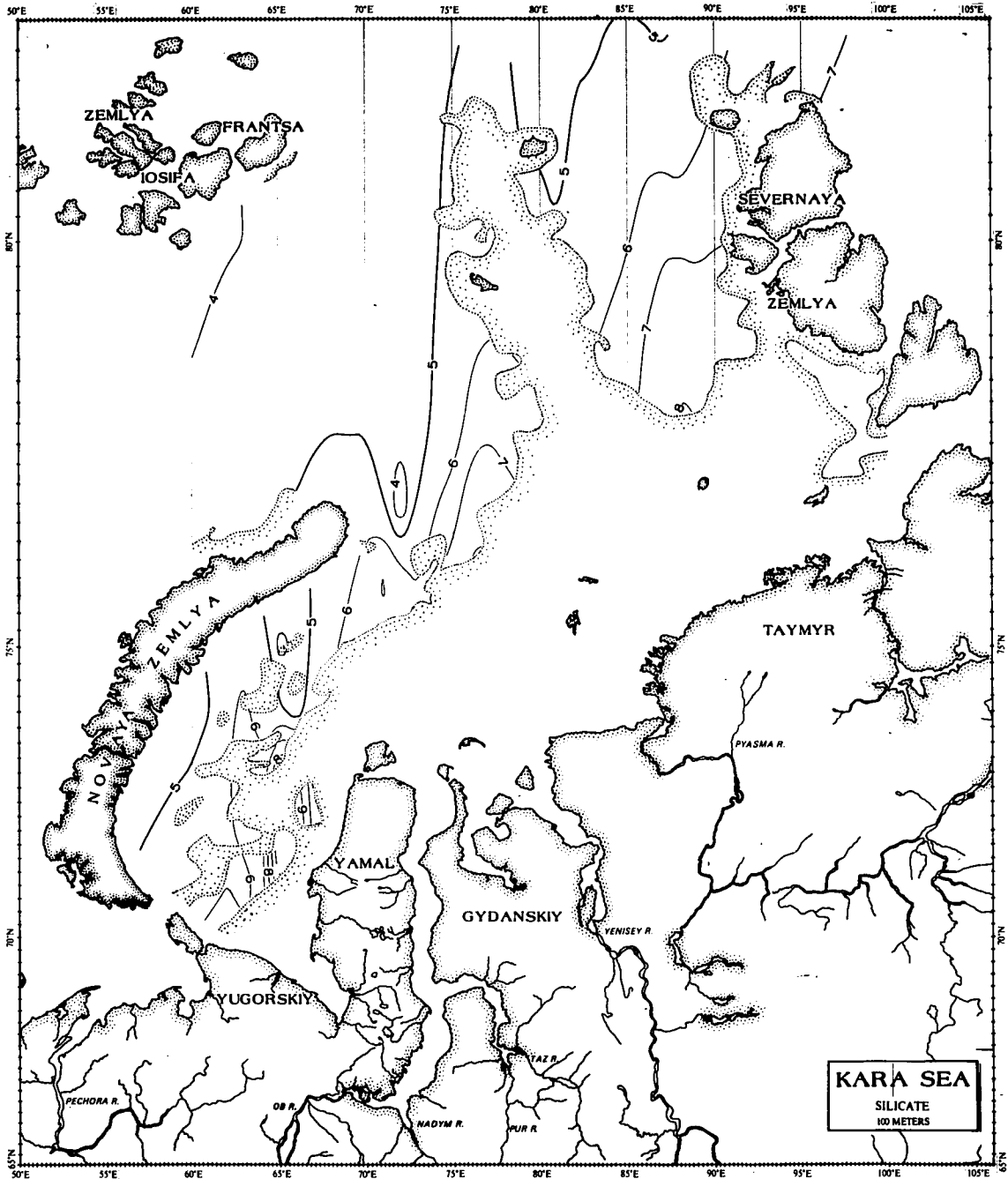


Figure B-26. Reactive silicate distribution in the Kara Sea at 100 meters. C.I. 1 µg-at/l

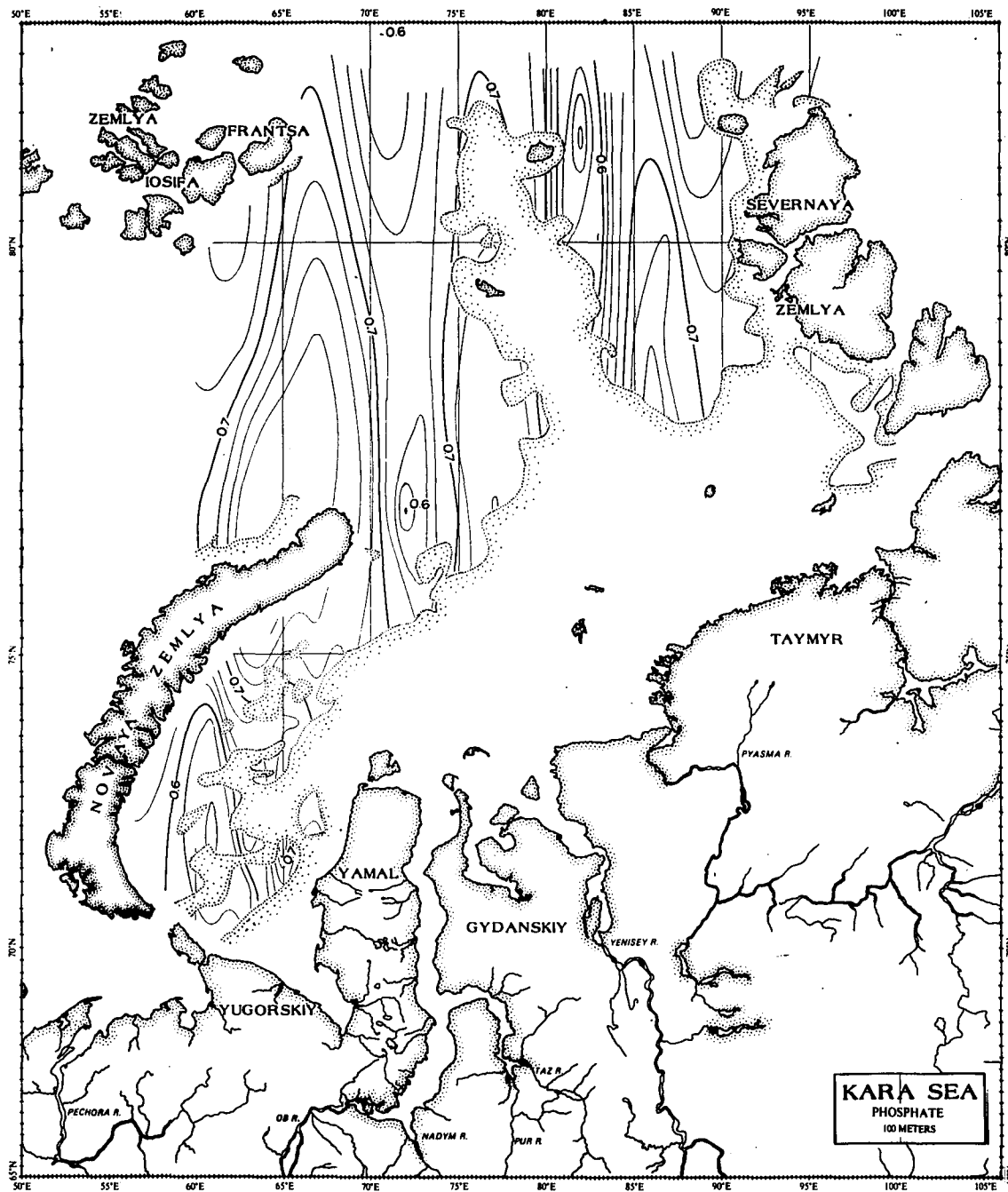


Figure B-27. Reactive phosphorus distribution in the Kara Sea at 100 meters. C.I. 0.025 $\mu\text{g-at/l}$

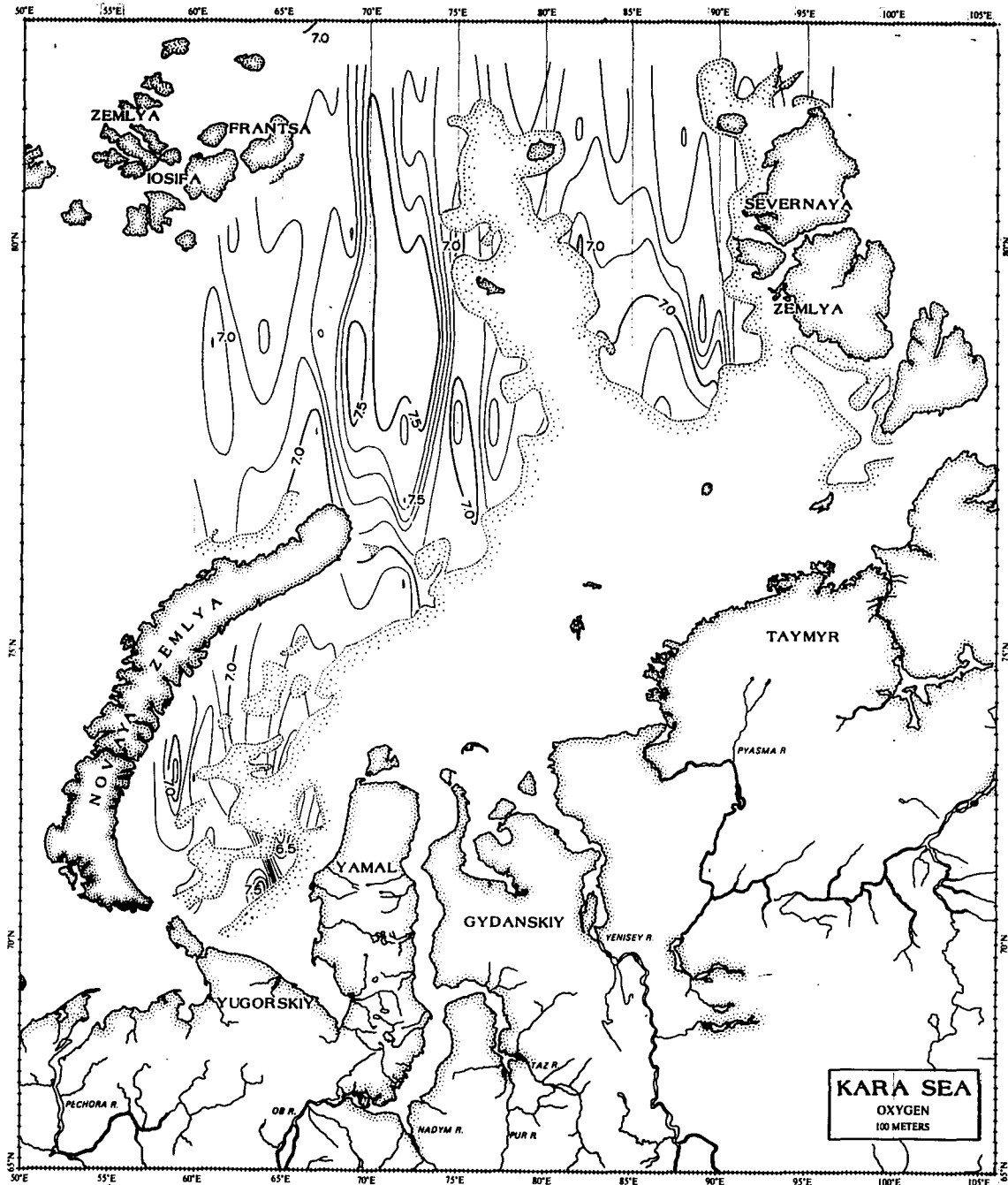


Figure B-28. Dissolved oxygen distribution in the Kara Sea at 100 meters. C.I. 0.1 ml/l

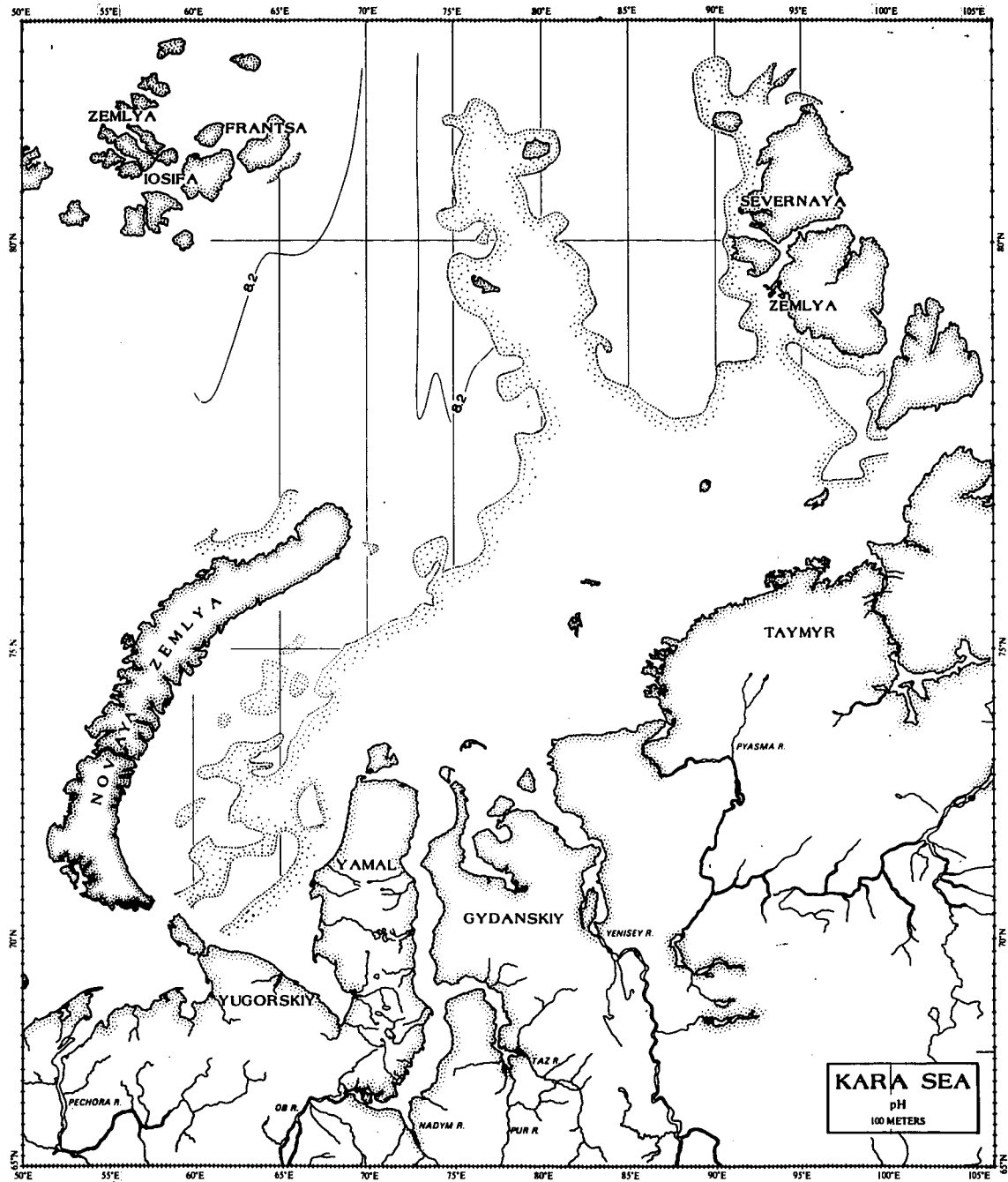


Figure B-29. pH distribution in the Kara Sea at 100 meters. C.I. 0.05

VITA

DONALD BRISTOWE MILLIGAN

Born in New York City, November 25, 1925. Graduated, Sylacauga High, Sylacauga, Alabama, May 1943; B.S. in Geology, Florida State University, Tallahassee, Florida, January 1956; M.S. in Marine Geology, Florida State University, December 1962; Ph.D. in Marine Science, College of William and Mary, August 1981. Dissertation: The Kara Sea: Geologic Structure and Water Characteristics.

Worked as a petroleum geologist in offshore Louisiana and Venezuela; as a field geologist in Alaska; and as an oceanographer for the Naval Oceanographic Office. Served on the staff of the Oceanographer of the Navy. Retired from the U.S. Government in 1980.